UiA University of Agder

Master

The Role of Hand Tracking and Spatial Scanning Based User Interactions in Immersive Technologies Supporting Active Learning

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AI Disclaimer

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Abstract

Virtual (VR) and mixed reality (MR) technologies continue to evolve, offering new opportunities for immersive educational experiences, particularly in museum environments where physical access to certain exhibits or environments may be restricted. Recent advances in user interaction modalities, such as hand tracking and spatial scanning, present promising possibilities for creating more natural, engaging, and memorable user experiences. However, their effectiveness compared to traditional controller-based VR interactions remains unclear yet. This thesis investigates how these emerging modalities can enhance presence, engagement, and memory retention in immersive educational contexts. Two proof-of-concept prototypes were developed: a stationary VR experience using controllers, and an MR experience incorporating hand tracking and spatial scanning. Both were situated in a realistic herbarium scenario developed in collaboration with the Natural History Museum in Kristiansand.

Following a human-centered design (HCD) approach, the study drew upon state-of-the-art literature and key theoretical frameworks, including embodied cognition, experiential learning, and Mayer's principles of multimedia learning, alongside preliminary user interviews with six museum visitors to validate requirements and interests. To evaluate the immersive prototypes, a qualitative-dominant mixed methods evaluation with 16 participants assessed user's perceived level of presence, engagement and memory retention through observations, questionnaires, and interviews. The study's findings are promising as both VR and MR user interaction modalities can effectively be designed to support active learning. However, it is evident that MR interactions led to increased presence and engagement due to their embodied and intuitive nature of user interactions, in contrast to VR, which was often limited by restricted movement and a challenging controller learning curve. While both prototype approaches supported short-term memory retention, the impact on long-term retention remains unexplored and presents an opportunity for future research. The study also identifies fundamental design decisions such as onboarding, multimodal guidance, and interaction clarity in supporting effective learning in immersive environments. These insights contribute to the design of meaningful, user-centered VR and MR experiences in educational and museum settings.

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Chapter 1

Introduction

As virtual and mixed reality immersive technologies evolve, particularly in terms of their interaction modalities, educational and cultural institutions are increasingly exploring innovative ways to enhance learning experiences. While virtual reality has been adopted for some time, mixed reality is now becoming more widely explored. These immersive technologies present powerful tools for education, offering learners the opportunities to visualize and explore complex subjects in intuitive and meaningful ways. By enabling users to actively engage with digital environments, effectively designed and developed virtual and mixed reality experiences can help support deeper understanding, greater immersion, and more memorable learning experiences.

Although the educational potential of these immersive technologies applies across many domains, they are particularly valuable in museum environments where certain collections or spaces are inaccessible to visitors due to preservation, safety, or environmental constraints. With the recent advancement of immersive technologies' hardware, namely the integration of room-scale spatial scanning and hand tracking features, there is a growing potential in creating more realistic, natural, and embodied learning experiences. As designers and developers, it is of interest to investigate and understand how these immersive technologies and emerging modalities, compared to traditional controller-based and stationary virtual reality interactions, can be purposefully applied to support meaningful, memorable and immersive learning experiences that facilitate learning, while providing a heightened sense of presence and engagement.

1.1 Background

The motivation for selecting this area of research originates from a personal passion in educational and immersive technologies, alongside an interest to deepen knowledge and expertise in the field. Recent advancements in immersive technologies' hardware and software have opened new possibilities for creating more engaging and innovative user experiences, not only in virtual reality (VR) but also mixed reality (MR). A further inspiration to explore mixed reality also revolved around a previous project that was developed in the course 'MM-505 Virtual and Augmented Reality' [76] named ManCave [59]. This is elaborated in chapter 4.1. Multimedia is evolving which presents exciting opportunities to bridge gaps in educational practices, enhance user engagement, and create interactive scenarios previously unattainable through traditional methods. Investigating these technologies in educational contexts, holds therefore a significant relevance not only in the context of 'Multimedia and Educational Technology' master's programme but also for the broader academic researchers who desire to expand the field and guiding the future development of immersive learning experiences.

The initial concept for the project's idea evolved through a collaboration with the Natural History Museum in Kristiansand. The museum highlighted the challenge of making its herbarium, housed in a controlled environment, accessible to the public, due to its strict preservation constraints and safety measurements. This led to the proposal of developing and designing an immersive virtual reality experience that digitally replicates the herbarium, enabling visitors to interact with the environment and learn about the herbarium and what is done there. Although plant collections are scientifically valuable, merely observing specimens in a museum environment often fails to engage visitors. An immersive, interactive experience can therefore transform a visit to the herbarium into an engaging, compelling and memorable learning opportunity.

Building on this foundation, further discussions with the supervisors emphasized the need to review the state-of-the-art of immersive technologies and its hardware. This examination would ground the project in current technological advances and help identify a focused, as well as relevant research direction. This review revealed the recent maturation of hand tracking and spatial scanning capabilities within the latest Meta Quest 3 hardware. [35] Therefore, it was decided to take two different scenarios of use: a controller-based, stationary VR experience and a room-scale MR experience employing hand tracking and spatial scanning. Both scenarios consider the herbarium use case, in order to have a clear understanding of which approach is most appropriate regarding the way users learn while creating an engaging and memorable immersive experience.

1.2 Target group

The target user group for this study comprises of museum visitors, with a particular focus on university students. Discussions with staff at the natural museum in Kristiansand revealed that a significant portion of their visitors are students from schools and universities. Therefore, in order to simplify the design focus, the target group were primarily university students at UiA in Grimstad Campus. Although the primary focus was on students, the general public visiting the natural museum was also included to ensure broader relevance and applicability of the project. Neither prior familiarity with immersive technologies nor herbarium-related topics and/or procedures were not a prerequisite for user participation in this study.

1.3 Scope and research directions

The scope of this master thesis project encompasses several parts, serving as a foundation to answer the research questions. Firstly, this study involves investigating educational immersive technologies in formal education as well as in museum-based educational scenarios. That includes designing and developing two functionally equivalent prototypes to support active learning in a herbarium setting. By following a Human-Centered Design (HCD) approach [17], the researchers consider the users at the center of the design process, making sure that the immersive products are designed to meet their needs and expectations.

Built in using the Unity game engine, the prototypes immerse users in scenarios within an herbarium environment, from learning about contamination measurements to preparing and pressing a specimen, taking DNA samples, and storage requirements. Although two different approaches are taken into the development of the prototypes, both versions recreate the same procedures, so that the learning content remains consistent while only the interaction modality varies. Additionally, the summarized and interpreted findings of user interviews taken at the museum with six participants, seen in Appendix I were used to validate requirements, interest in the topics, and technologies chosen as part of the human-centered design approach. This did not only help getting to know the target audience better, but what expectations they have as well as what they value and desire most in a possible educational interactive product at the museum. The design decisions made will be discussed in terms of their effectiveness with the goal of answering research question one.

Secondly, this work involves studying users' perceived presence and engagement as they interact with the designed prototypes experiences, and how the different interaction modalities implemented influence the users' experience. When understanding what approach and interaction decisions are best when it comes to learning contexts, it is fundamental for VR and MR designers to consider the users perceived level of presence as it indicates whether the user feels present in the experience and wants to be engaged in it. Presence refers to the feeling of 'being there' and is related to the user's inner psychological state [18]. A failure in creating a sense of presence in the experience will reflect in demotivation and detach the user from the experience. Further, maintaining user engagement is equally as important, as it reflects the user's sustained attention and emotional involvement in the experience. Therefore, it is also important to look at engagement and ensure that the interactions in the immersive experiences remain intuitive and rewarding, so that users stay focused and invested throughout the learning experiences.

Beyond presence and engagement, memory retention is a key factor in educational experience's effectiveness. Without adequate immersion and engagement, the learning experience can be compromised, and the amount of information users are able to retain is greatly diminished. By therefore examining how these two prototype approaches and its interaction methods decisions influence what users remember, researchers can determine whether the immersive system(s) truly facilitates learning rather than simply providing a novel encounter.

1.4 Problem statement, objectives, research questions & hypothesis

1.4.1 Problem statement

Traditional virtual reality interactions, such as controller-based input and stationary navigation may limit users' experience in terms affecting the senseof presence, natural engagement, and memory retention in learning environments. Museums, in particular, often aim to create participatory learning experiences, yet many digital exhibits still rely on passive modes of engagement, such as reading static text or observing visuals without interaction. The same can apply to education where learning approaches often involve reading and listening to a lecturer without involving any sort of physical interaction with the content. In contrast, recent research in education highlights the benefits of active learning, where learners construct knowledge through meaningful interaction, reflection, and sensory engagement [63]. With the introduction of advanced capabilities in modern head-mounted devices (HMD) like the Meta Quest 3, such as spatial scanning and hand tracking, there is an opportunity to design more immersive, intuitive, and embodied learning experiences that support active exploration and deeper cognitive processing. These emerging interaction modalities may promote more immersive experiences, potentially leading to improved engagement, stronger presence, and enhanced recall of information.

However, it still remains unclear whether these new interaction modalities provide significant educational benefits over traditional controller-based virtual reality approaches. This research addresses this gap by evaluating how hand tracking and spatial scanning in mixed reality influence user experience, engagement and learning effectiveness, in comparison to stationary, controller-based virtual reality. Although this study is situated within a museum educational scenario - intended for a digital herbarium - the findings aim to inform broader applications of immersive technologies in active learning contexts.

1.4.2 Objectives

- To investigate current gaps and opportunities for active learning, supported by immersive mixed and virtual reality technologies.
- To design and develop two interactive prototypes supporting active learning in a herbarium setting: one using virtual reality stationary and controller-based interactions and another one using mixed reality hand tracking-based interactions and spatial scanning.
- To evaluate the influence of the user interaction methods on the user's perceived sense of presence and engagement.
- To assess the impact of these interaction methods on the user's memory retention, focusing on task-based learning activities.

1.4.3 Research questions

RQ1 - How can mixed and virtual reality experiences be effectively designed and developed to facilitate active learning in educational and museum environments?

RQ2 - To what extent does hand tracking and spatial scanning influence the users' perceived level of presence and engagement in the mixed reality experience compared to virtual reality interaction methods?

RQ3 - How do the different interaction modalities affect memory retention after using the immersive experiences?

1.4.4 Hypothesis

H1 - The continuous perception of objects in the real physical world has a positive impact on the immersive experience within mixed reality interactions.

H2 - In VR supported scenarios, the retention is positively affected by being in a stationary setting.

H3 - Physically navigating around a dedicated space in the mixed reality experience leads to higher engagement.

1.5 Limitations & constraints

Several limitations and constraints affected the development and evaluation of the immersive prototypes used in this study. Firstly, the project was limited to only two Meta Quest 3 headsets, with no available backups. This presented a risk during both development and user testing, as any hardware failure could not be immediately mitigated.

Secondly, time constraints imposed by a single semester schedule required the development of two fully functional prototypes within a compressed time frame. Balancing the design, development, and evaluation phases within such a period limited the opportunity for iterative refinement and extended user testing.

Thirdly, access to relevant 3D models posed a production bottleneck. Many of the assets required for the prototypes either did not exist or required significant optimization. While some assets were sourced from online repositories, most had to be modeled and textured from scratch, and even premade assets often required rebuilding for the sake of performance optimization to run efficiently on the Quest 3's standalone hardware.

Fourthly, the target audience for the prototypes initially consisted of the general visitors to a nature museum. However, due to geographic distance and scheduling challenges, usability testing was primarily conducted with university students, which may have influenced the evaluation results and limited insights into the intended broader public user group.

Another challenge was the difficulty in sourcing relevant academic literature, due to the rapidly evolving nature of immersive technologies research. Many existing studies were either outdated or not directly applicable to the latest hardware and interaction methods used in this project.

Finally, although the Meta Quest 3 is currently the most advanced headset in the Meta product line, it suffers from some technical limitations. These include inconsistent hand tracking, which at times caused user interactions to go undetected, and frequent issues with uploading or restoring scanned room data, occasionally impacting MR functionality. These technical instabilities introduced unexpected obstacles during both development and user testing.

1.6 Thesis structure

This thesis follows a structured outline, with each chapter serving a specific purpose to contribute to the research topic. After the introductory chapter, follows chapter 2, which delves into the state-of-the-art, conceptualizing relevant theories to the study as well as an overview of what has been done in the field of immersive technologies and its interaction modalities in learning contexts, such as in museums as well as in the broad context of education. Further, chapter 3 describes the methodologies utilized to gather and analyze data. Chapter 4 will delve in detail regarding the design and technical development of the immersive experiences prototyping, following design principles and a human-centered design approach. The results and findings are explained, summarized and illustrated in chapter 5, answering each specific research question. To finalize, chapter 6 concludes the thesis based on the findings from chapter 5, with eventual recommendations and notes of possible improvements and future work.

Chapter 2

State-of-the-art

This chapter provides an overview of the state-of-the-art in immersive technologies as well as its technological and historical development, emphasizing recent advancements relevant to educational applications within museum scenarios and in the broader educational sector. Further, the focus is particularly on innovative interaction modalities intended for immersive technologies that can be integrated for the design of experiences to facilitate learning, specifically spatial scanning and hand tracking. Foundational concepts such as presence, immersion, and engagement within immersive environments are discussed, alongside learning theories, active learning frameworks and memory retention aspects related to Mayer's multimedia learning principles [33]. This comprehensive review aims to identify key factors, informing the research presented in this thesis and highlighting potential areas for new contributions.

2.1 Immersive technologies

Immersive technologies, often related to the term 'extended reality (XR)', encompasses a broad spectrum of interactive environments designed to create varying levels of realism by blending digital and physical realities. These are technologies that amplify and extend our 'natural senses' ranging from our sight to our sound and touch, by substituting digital information in real time [45]. By enriching what we see, hear and feel, these immersive technologies create compelling experiential spaces that can transform learning, training, and everyday interactions. There are several modalities that comprise immersive technologies. In order make these modalities more understandable and concise, the Reality-Virtuality Continuum [41] illustrated in figure 2.1, explains this briefly. At one end there is the real world environment where no immersive technologies related elements are in use, while on the opposite end is a fully synthetic, immersive world where all perception is virtual and users are able to feel immersed and present in a digital environment [66].

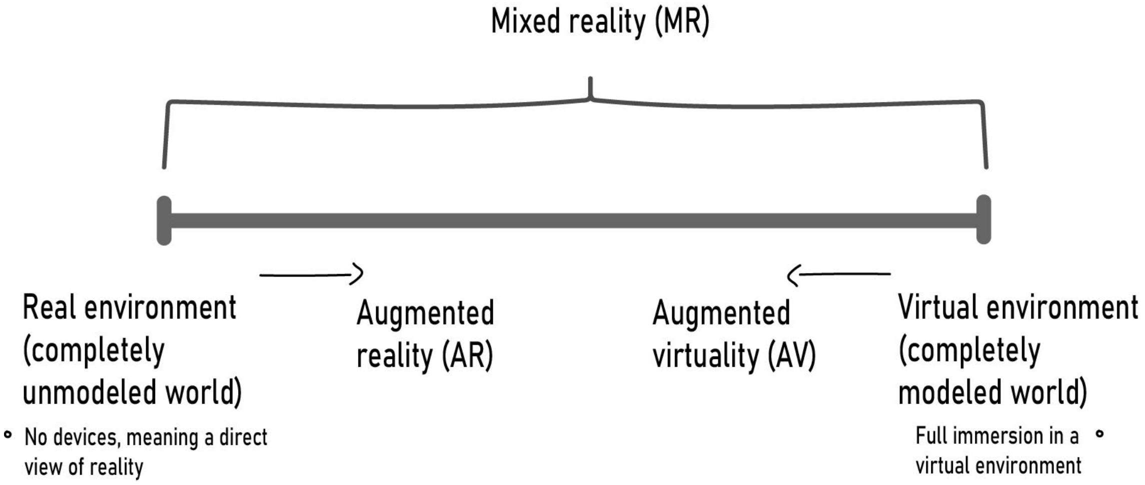

Mixed reality (MR)
Real environment (completely unmodeled world)
No devices, meaning a direct view of reality
Augmented reality (AR)
Augmented virtuality (AV)
Virtual environment (completely modeled world)
Full immersion in a virtual environment

Figure 2.1: Reality-Virtuality Continuum, adapted from [66]

XR is an umbrella term that covers three foundational modalities : Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). VR is an immersive artificial environment replacing the physical reality, where users feel present and immersed in a completely virtual realism [18]. AR is a real-time interactive digital technology that supplements objects in the physical world with digital elements, being an overlay over the actual world environment [18]. MR is when the digital and real world are combined, providing opportunities for interaction with the virtual and physical objects simultaneously.

2.2 The historical & technological development of VR & MR

The origins of immersive technologies can be traced back to optical innovations such as panoramic paintings [83] and stereoscopes [25], which aimed to create illusions of depth and presence. These early attempts evolved into more complex multisensory systems like Morton Heilig's Sensorama and Telesphere Mask [6], which introduced audiovisual immersion and rudimentary interactivity. A major turning point came with Ivan Sutherland's Sword of Damocles [6] in 1968—the first head-mounted display system that integrated computer-generated graphics and real-time tracking, laying the foundation for interactive virtual environments. These milestones marked the gradual shift from passive visual tricks to actively generated, responsive digital spaces—paving the way for modern virtual and mixed reality systems.

Modern VR and MR technologies build on this legacy with significant advancements in processing power, display resolution, tracking precision, and interaction design. Today's standalone headsets like the Meta Quest 3 [35] and Meta Quest Pro [36] feature inside-out tracking, full-color pass-through, spatial mapping, and hand tracking, enabling untethered, embodied interaction within physical environments. Natural input modalities such as gesture recognition, voice control, and eye tracking have increasingly replaced traditional controllers, allowing for more intuitive and immersive user experiences. These capabilities have broadened the application of VR and MR across fields such as education and cultural heritage, where the focus has shifted from visual immersion alone to active, engaging, and embodied learning.

2.3 Presence, immersion, & engagement in immersive environments

The effectiveness of both VR and MR experiences is strongly affected by the sense of presence of the users involvement in the experiences. The user's sense of presence can be defined as the feeling of "being there", despite still remaining physically in the real world [69]. This psychological state is not generated by one single factor but emerges from a combination of sensory immersion, system responsiveness, and cognitive coherence. Although users are aware on a rational level that the environment is artificial, the combination of realistic visuals, spatial audio, and embodied interactions can deceive the brain into responding as though the experience was authentic. The degree of presence experienced often depends on where the user's attention is focused, for example the more the user concentrates on the virtual environment, the stronger their sense of presence becomes. Although this feeling can emerge in fully virtual environments, it can also emerge in mixed environments, where digital content is blended with the physical world [69].

Engagement builds upon these foundations. It reflects the user's cognitive, emotional, and behavioral involvement in the experience. When users are able to feel that sense of "being there", they are more likely to invest their attention, explore actively, and therefore connect emotionally with the content. Factors such as inclusiveness, narrative structure, attentional demand, emotional resonance, task interactivity, and the degree of presence all contribute to shaping the overall sense of engagement [69].

2.4 Active learning approaches

Learning revolves around diverse theoretical approaches. Some individuals have certain learning preferences that others do not, whether it is listening, writing or engaging with the content in different ways. There are certain opinions on what exactly conceptualizes the term 'active learning', and some recall it as the act of learning by doing in regards to a specific action or activity [63]. Active learning emphasizes strategies and certain characteristics by placing the learners at the center of the process and redefining the role of the educator as a facilitator rather than a transmitter of knowledge. This means that learners are rather engaged in the process of learning through activities, therefore increasing their higher order of thinking as compared to passively listening to an educator. According to Sewagegn and Diale [63], active learning is grounded in the belief that knowledge is best acquired through experience, reflection, and engagement rather than passive absorption of information.

2.4.1 Embodied cognition

There are different active learning approaches that shape the way individuals learn. Embodied cognition emphasizes that cognitive processes are deeply rooted in the body's interactions with the environment, suggesting that the mind is not separate from the body, but rather shaped by it [19]. This perspective emphasizes that thinking, understanding, and learning are influenced by sensory input, bodily movement, and motor activity. Wilson [84] outlines six key views of embodied cognition, each highlighting different ways in which cognition is constrained or enabled by the body and its movements. For instance, when learning by physically manipulating objects, as oppose to reading or observing, engages therefore multiple sensory and motor systems that reinforce conceptual understanding, meaning that our physical actions, gestures and environmental interactions play a central role in how we understand, remember, and apply knowledge. Glenberg and Gallese [12] point that cognition is not just situated in the brain but is distributed across the entire body, emphasizing the role of sensorimotor systems in conceptual processing. This underscores therefore the importance of physical engagement and environmental context in learning, meaning that knowledge acquisition can be enhanced when learners actively interact with their surroundings [19].

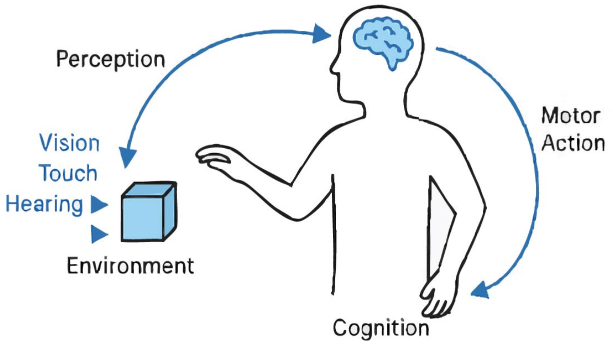


Figure 2.2: The role of the body in cognition, adapted from [84]

2.4.2 Experiential learning

Closely aligned with the principles of embodied cognition is the theory of experiential learning, which on the other hand positions experience as the central component in the process of learning. Originally proposed by David Kolb [26], experiential learning theory conceptualizes learning as a cyclical process, illustrated in figure 2.11, revolving around four main stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation. According to Kolb, knowledge is not transmitted from an educator to the learner but rather created through the transformation of experience into understanding [26]. For instance, in a traditional classroom setting when learning about plants in a biology class, instead of merely reading about plant anatomy, learners might on the other hand engage in a hands-on activity such as dissecting a flower. Thereafter reflect and apply learned procedures into broader theoretical concepts, deepening their understanding through direct experience. It overall supports the idea that learning becomes more effective when learners are immersed in activities that challenge them to think critically, adapt, and apply based on attained knowledge.

This approach can furthermore be particularly relevant in the context of immersive VR and MR technologies. Concrete experiences in these technologies can for example be created through first-person interactions in immersive virtual environments. Further, reflections can be guided through integrated feedback within the system such as a virtual quiz or feedback based on wrong choices within the scenario of use. Additionally, reflections can be made post-experiment in form of an oral test. Abstract conceptualization can be encouraged through scaffolded learning tasks while active experimentation is naturally supported as users manipulate objects, and learn by doing. In this way, immersive experiences not only place learners at the center of the action, but also allow them to enagge with content in a way that is iterative, exploratory, and content-rich. This dynamic, learner-centered approach mirrors the embodied cognition principle that knowledge emerges from interaction with the environment rather than observing or reading.

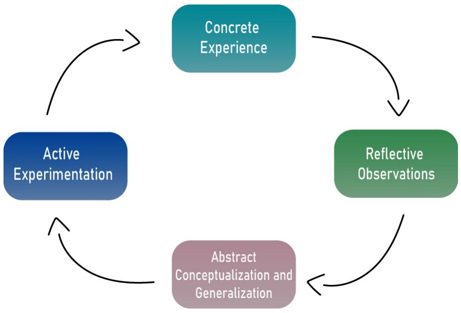


Figure 2.3: Kolb's experiential learning model, adapted from [26]

2.4.3 Kinesthetic learning & multimodal preferences (VARK)

Understanding how individuals engage with and absorb information is fundamental when designing educational experiences intended for immersive technologies. As mentioned, each individual is different in regards to learning preferences and styles. One influential framework example, in addition to Kolb's experiential learning model, for categorizing learning preferences is the VARK model, which classifies learners into four primary modalities: Visual, Auditory, Reading/Writing, and Kinesthetic. According to Wintergerst in Yusoff [49], there are individuals who have more than one type of learning styles, known as bimodal. While many individuals benefit from a combination of these models, kinesthetic learners tend to excel when learning involves movement, physical activity, or hands-on engagement [49].

Kinesthetic learning is particularly relevant in interactive VR and MR environments, where the potential for bodily interaction is high. Learners with kinesthetic preferences often rely on spatial awareness, gestures, or physical movement to understand and remember information. A study by El-Sabagh et al. [60] found that accommodating different learning styles, including kinesthetic, can enhance engagement and learning outcomes in technology-mediated environments. In VR immersive experiences, where locomotion can be a constraint, such as restricted movement or reliance on teleportation may affect the learning experience of kinesthetic learners who instinctively try to interact through physical motion.

2.5 Memory retention - Mayer's priciples of multimedia learning

Memory retention is an important aspect of effective learning. The term typically refers to the amount of information an individual can recall over time, encompassing both short-term and long-term memory. In VR and MR immersive environments, memory retention can be influenced by the learner's level of engagement, the degree of sensory involvement, as well as the meaningfulness of the experience. Mayer's principles of multimedia learning [33] suggests that immersive learning environments and the integration of multimedia elements can enhance one's retention by promoting active, embodied interactions, which helps learners remember the information better.

In contrast, a poorly designed experience can lead to cognitive overload. A study by Parong and Mayer [50] on 88 college students, compared an immersive VR experience, employed in the Oculus Rift, with a desktop-based slideshow presentation on how the human body defends itself against pathogens [50]. Although the VR group reported higher interest and engagement, the desktop group performed better on memory retention and transfer test, which clearly suggests that poorly designed immersive content can overwhelm the learners and distract them from the learning content [50].

2.6 VR & MR in immersive learning

Designing and developing immersive experiences is an ever-evolving challenge, continuously driven by rapid advancements in virtual and mixed reality technologies. Today, they are currently being used across diverse fields including education, healthcare, architecture, engineering and training [27]. As these tools become more accessible and sophisticated, is has opened new possibilities for enhancing learning, engagement, and exploration. This section will go over how immersive technologies are being used in educational contexts as well as in museum environments.

2.6.1 VR & MR in education

Virtual reality has been explored for some time, becoming widely adopted in education. Although immersive technologies have gained increased attention in recent years, they remain however still quite novel [27]. Hardware devices such as virtual reality head mounted devices (HMD) are not yet widely adopted by the general public, and their integration into formal learning environments is still limited. Mixed reality on the other hand, remains a relatively recent development in both education and other domains where fewer studies have been conducted. Although the literature is still expanding, several studies have begun to investigate its potential and effectiveness.

A study by Bodzin et al. [8] involving 54 adolescents aged 16-18 from an urban school in the United States, designed and implemented an immersive VR game aimed at enhancing environmental science education among high school students. The VR module, displayed on the Oculus GO HMD, focused on teaching students about their local watershed [8]. The findings revealed that all students experienced a high level of engagement during the VR learning activity. Additionally, 98.1% of the students reported positive attitudes toward using the VR game, noting high levels of immersion and presence. It was found that these results suggest that immersive VR experiences can significantly enhance student engagement and foster positive attitude toward learning in educational environments [8].

Furthermore, a study by Makransky et al. [31] investigated the impact of immersive virtual reality (IVR) simulations on student's interest, self-efficacy, and career aspirations in the subject of science. It was conducted two separate studies, where the first involved lower secondary school students engaging in a VR-based laboratory safety simulation, while the second focused on comparing high school students learning about DNA analysis through either an IVR simulation or a traditional video [31]. The results, involving 99 participants aged 13-16 showed that students who participated in the VR experiences demonstrated significantly higher levels of interest in the subject and increased self-efficacy as well as retention related to scientific tasks [31]. In the second study, involving 131 high school students aged 17-20, the IVR group exhibited greater gains in interest and perceived social outcomes compared to the video group [31]. These findings support the idea that IVR can go beyond novelty, offering measurable educational benefits such as higher engagement, stronger self-belief, and deeper interest, especially in such subjects often seen as more challenging.

As mentioned previously, mixed reality is still quite novel in terms of research and applicability compared to virtual reality in education. However, some studies have started to emerge to understand its effectiveness as an educational tool. One study by Almufarreh [2] investigated the impact of mixed reality on 308 students' academic performance and learning experiences using the Microsoft HoloLens 2 HMD [2]. The experiences were designed to enhance student's understanding of complex concepts through interactive simulations, where 3D holographic content was placed onto real world surfaces. This allowed for hands-on learning experiences that transformed challenging theoretical content into experiential learning. It was found that the use of mixed reality provided an overall positive and engaging experience, leading to improved comprehension of subject matter as well as heightened motivation to learn.

Another study by Moro et al. [43], employing the HoloLens 2, investigated the effectiveness of mixed reality in teaching anatomy to medical and health science students. 38 pre-clinical undergraduate participants completed a lesson detailing the physiology and anatomy of the brain. Here, it was compared traditional learning methods with mixed reality-enhanced instruction to access the differences in learning outcomes. Students that participated in the study engaged with 3D holographic models, allowing them to spatially explore and interact with the anatomical structures of the brain. This was further compared to a control group which utilized traditional instructions [43]. The results showed that the group using mixed reality exhibited significantly stronger spatial understanding of anatomical relationships and reflected higher engagement and motivation during the learning process. Feedback from the student participants also indicated that the mixed reality experience was not only more enjoyable but also helped them gain a deeper and more intuitive understanding of the content [43]. These findings reinforce and strengthen those reported by Almufarreh's study [2], further supporting that mixed reality can definitely enhance learning outcomes by fostering engagement, improving comprehension on complex topics, while also providing an active and experiential experience.

2.6.2 VR & MR in museums

While virtual and mixed reality have shown considerable promise in education, their adoption in museum environments has also began to grow and create interactive exhibitions that go beyond static displays, allowing visitors to, for instance, explore historical reconstructions, examine artifacts in 3D, or engage with narrative-driven simulations. Since the prototypes developed in this research are intended for a potential future museum exhibit, it is important to explore how similar immersive technologies have been integrated in previous museum studies.

A recent study by Schlachhoff et al. [61] introduced 'RHINO-VR', a virtual reality reconstruction of the RHINO autonomous tour guide robot that originally operated in the Deutshes Museum Bonn in 1997. Developed in Unity and deployed on the Meta Quest 2 HMD [61], the experience allowed visitors to explore a virtual museum environment while observing and interacting with RHINO as it navigated autonomously, explained exhibits, and demonstrated sensor-based behaviors in order to help users understand how the robot 'sees' and makes decisions in real-time. The purpose of the project was both historical preservation and educational enhancement, aiming to teach users about mobile robotics in an engaging and immersive way. A user study involving 20 participants found that RHINO-VR promoted high levels of engagement, presence, and educational value. Further, results showed that the VR experience promoted exploration as users were encouraged to freely navigate the virtual museum and engage with robotics concepts at their own pace. Participants ended up reporting a better understanding of robotics concepts and generally rated the experience as intuitive and enjoyable, though minor user interface adjustments were suggested [61]. These findings demonstrate how virtual reality can be effectively applied in museum learning environments to support experiential learning through embodied interactions.

Furthermore, mixed reality has also begun its integration into museum environments. A study by Glinka et al. [13] investigated the use of mixed reality in a museum environment through a prototype developed for the HoloLens. The system overlaid interpretive digital content onto physical sculptures, enabling visitors to engage with exhibits and artworks through intuitive gaze-based interaction. The researchers examined how different modes of activity (e.g., passive vs active observation) and modes of guidance (e.g., linear vs user-driven) influenced visitor experience [13]. Findings from user observations and interviews revealed that mixed reality supported non-linear, self-directed exploration while enhancing engagement and time spent with the exhibits. Participants reported that the mixed reality experience encouraged closer observation and reflection by layering information in a way that allowed for self-paced learning [13]. By therefore blending physical and digital elements in ways that support deeper cognitive and sensory involvement, mixed reality has definitely the potential to enhance museum exhibits interactions as well as participants' engagement

2.7 Interaction modalities & design for active learning in immersive environments

As immersive technologies evolve, so do the ways in which users interact with the digital content. When designing and developing educational immersive experiences intended to facilitate learning, the interaction modalities play a fundamental role in shaping how learners engage with, explore, and remember information. Without interactions, the experience won't come past a passive observation where the user's most likely won't have anything to do, which defeats the whole goal of being active in learning. Recent emerging modalities such as hand tracking and spatial scanning have the opportunity to offer more natural and embodied forms of interaction compared to traditional controller-based and stationary-based inputs. These modalities not only have the ability to increase realism but also give learners greater control and freedom in how they interact with the virtual environment, encouraging therefore participation, exploration, and hands-on engagement. This section will go over current studies on how previous research has evaluated and integrated such interaction modalities in their studies and how such modalities are able to have a positive influence on user experience as well as achieved learning outcomes. Further, other elements such as navigation, audio, text and visualization are explored to understand their impact in studies for the design of an effective immersive learning experience.

2.7.1 Interactions - Hand tracking & controller-based

Hand tracking is the ability to use our own hands to virtually engage with the environment, facilitated by HMD's cameras and sensors. While traditional virtual reality approaches may utilize controller-based inputs with limited gestures and interactions, hand tracking on the other hand can give a more natural and freely way of interaction.

Voigt-Antons et al. [79] conducted a study comparing hand tracking and controller-based interactions in virtual reality using the Oculus Quest and Leap Motion for hand tracking input. The experiment involved 27 participants, where users performed object manipulation tasks using both interaction methods. The first task revolved around sorting five red and five blue balls by grabbing them and putting them in the correct box, while the second task was to retype displayed number sequences on a virtual numerical keyboard [79]. The results showed that hand tracking was perceived as more natural and intuitive, contributing to a stronger immersion. However, participants also noted reduced precision and occasional tracking instability, which negatively affected the task performance. In contrast, controllers were viewed as more reliable and better suited for precise interactions [79].

A study by Varela-Aldas et al. [77] went in depth regarding whether hand tracking in an immersive virtual reality experiences has any measurable influence on memory performance assessment compared to controller-based interactions. Using the Meta Quest 2, 20 participants aged 18 to 60 completed daily-based activities where users had to remember the location of the elements [77]. This tasks involved a virtual kitchen environment where users first observed the placement of the items inside the cabinets, and were later required to recall and select the correct cabinet doors, using either hand tracking or controllers within a limited time. Errors were then recorded for incorrect or delayed responses. The researchers further measured response time, task accuracy, perceived presence, usability and satisfaction. Results showed no statistically significant differences between the two interaction modalities. In fact, the controller-based approach showed slightly higher accuracy and faster response times, while presence, usability and satisfaction scores were nearly identical between both approaches [77]. Contrary to expectation, hand tracking did not improve memory performance or subjective user experience in this context, suggesting that its benefits may be depend on the type of task and that is not always better than traditional methods in memory activities [77].

2.7.2 Navigation - Spatial scanning & teleportation

While interaction modalities influence how users manipulate and engage with content, navigation techniques shape how users move through and perceive virtual environments. Users can for example teleport while being in a stationary position or for example by physically move around a dedicated scanned space.

For instance, a study by Rey et al. [54] investigated how different navigation methods have an influence on user experience and task performance in an immersive world-cloud visualization. 14 participants using the Meta Quest 2 performed a task that required locating and ordering the four most relevant words based on visual cues. The findings showed that participants in the room-scale walking approach had better recall of words, interacted more and reported a higher confidence in regards to their performance [54]. However, they also experiences a higher mental workload compared to those using teleportation, who managed to complete the task with similar accuracy and less physical work [54]. Such findings emphasize that while room-scale walking can foster active exploration and short-term memory, it may also demand more cognitive and physical resources, highlighting that more realistic navigation can improve memory and engagement but may also be more tiring or mentally demanding than simpler movement methods.

2.7.3 Audio & text

Furthermore, in addition to such interaction modalities, other aspects to keep in mind when designing an effective immersive experience are audio and text elements. These elements are often required in order to convey the learning material to learners. However, it is important to create an appropriate balance between these, so that it does not end up overwhelming and distracting the user from the learning activities. A study by Moreno and Mayer [34], investigated whether presenting the same information as both audio narration and on-screen text hinders or facilitates learning. Interestingly, learners understood the content more effectively when audio narration was utilized instead of on-screen text, additionally when combined with animations [34]. Presenting both animations and text simultaneously overloaded the visual channel of working memory, reducing learners' ability to process and integrate information. As mentioned, in contrast, audio narration utilized the verbal channel, freeing up visual resources and promoting better retention as well as understanding [34].

2.7.4 Visualization

Designers and developers can take different approaches when designing the visuals of an immersive experience, depending on what the concept and learning goals are. These can be realistic, cartoonish and low-poly. However, it is usually better to opt for realistic visualizations in educational learning as they can enhance immersion and spatial understanding, especially when the goal is to replicate real environments. According to a systematic study by Gonçalves et al. [14], it was reviewed that higher visual realism generally enhances the user's sense of presence and immersion. However, its influence on learning and task performance was inconsistent and often depended on the context and cognitive demands of the activity [14]. In some cases, simplified visuals can lead to better outcomes by reducing visual complexity and cognitive load. Meaning that while realistic visuals can enrich immersive learning experiences, their effectiveness depends on aligning visual fidelity with the educational goals and mental demands of the task [14].

Take for instance the study by Makransky et al. [31] which was explored in section 2.6.1. In this study, a highly realistic virtual reality science lab simulation was compared to a desktop version of the same content. While the realistic visuals of the immersive environment had a positive influence on the users' sense of presence, it in contrast resulted in lower learning outcomes. This was attributed to the added cognitive load which was increased by the immersive visuals, emphasizing that although realism can enhance engagement, it may also hinder learning if not appropriately balanced with the task's cognitive demands.

Chapter 3

Methodology

This chapter outlines the methodological approach adopted for the study, explaining how data was collected, analyzed, and validated. The experimental setup follows on a human-centered-design process, describing methods used to create the immersive experience prototypes, including an overview of the the data gathering methods. A qualitative dominant mixed methods approach was employed encompassing in-depth pre- and post-test interviews, observations, and questionnaires. Additionally, this chapter also addresses ethical considerations and the rationale for using qualitative analysis as a methodology. A thematic analysis was used to interpret and analyze the collected data.

3.1 Experimental setup - test environments

The experimental setup for the user studies involved two controlled environments, namely the Future interaction lab at the University of Agder in campus Grimstad, and the museum at the natural museum in Kristiansand which took place in the staff offices. During the course of two weeks in April 2025, user testing was conducted with sixteen participants across two iterations of the prototypes. Since different participant groups were needed for each prototype, two separate tests were conducted per iteration. For a clear understanding, a table will be illustrated in section 3.2.3 where the participant groups division is further elaborated. Each test was conducted with one participant at a time, and lasted for 60 minutes. The tests firstly started with a five minute pre-test interview, followed by three minutes of instructions on how to control and equip the Meta Quest 3 head-mounted device. Further, 30 minutes were allocated for the user tasks and observations. During this phase, the participants were observed as the prototype was used where different user tasks were completed. Observation notes were taken digitally on a laptop while the immersive experience was being showed on an external screen. After the observation phase, it was allocated ten minutes for two pre-test questionnaires, one including the System Usability Scale (SUS), where the observers left the room while the questionnaires were being taken. Lastly, there was a 10-15 minute post-interview that reflected and went in-depth on the participant's experiences and recall of information. The full interview guide for user testing can be seen in Appendix B

The physical setup of both testing environments were allocated to ensure that participants had sufficient space to move freely and safely, minimizing the risk of colliding with the physical world. The testing space consisted of a table, a laptop, and an external screen used by the observers. Any external objects such as chairs or miscellaneous objects were moved aside to stay outside of the defined boundaries of the immersive experiences. Additionally, the researchers ensured that both testing environments had adequate lighting, particularly important for the mixed reality prototype, which depended on natural and sufficient ambient light to maintain accurate tracking of hand and head movements.

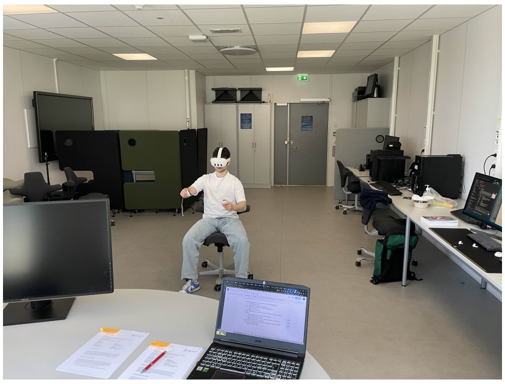


Figure 3.1: Experimental setup test environment for VR prototype: controller-based user interaction, stationary (Picture: the researcher, not a real participant)

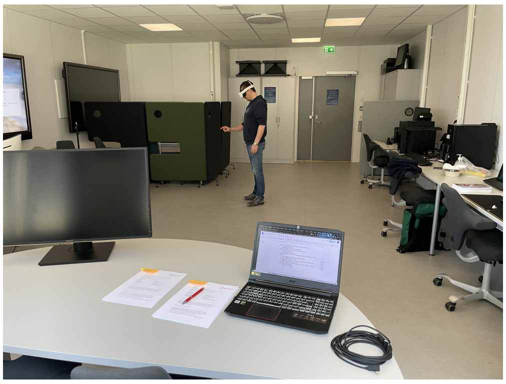


Figure 3.2: Experimental setup test environment for MR prototype: hands-based user interaction, spatial scanning(Picture: the researcher, not a real participant)

3.2 Ethical considerations

Ethical considerations are a fundamental aspect to keep in mind in any user-centered research study, ensuring the protection of participant's rights, safety and data collection. In this study, all participants were informed with a consent form [56], which can be seen in Appendix E, about the purpose of the study, procedure of the usability test, their voluntary involvement, how data is collected and processed, as well as their right to withdraw at any time. Informed consent was obtained prior to participation, and no personally identifiable information was collected or stored. Addressing ethical principles helped maintain transparency and build trust throughout user testing.

3.3 Data gathering

Data gathering is a fundamental step in a research study process utilized as a foundation to answer the research questions of the study. It provides objective information needed to evaluate outcomes, make informed decisions, guide improvements and generate valid conclusions. By understanding who will use and overall be affected by the product, known as the stakeholders, the researchers can gain valuable insights into user needs, expectations, and potential challenges.

3.3.1 Human-centered design process

The project followed a human-centered-design (HCD) approach [17] to ensure that the herbarium immersive experiences designed were grounded in the needs, expectations, and contexts of the end-users. A HCD approach is an iterative design process that prioritizes usability and user ergonomics by placing the users at the center of the design, ensuring that solutions are tailored to their needs in order to create solutions that are usable, useful and meaningful [17]. By including the users throughout the the whole design process, the researchers can ensure that potential usability issues are identified and effectively addressed. A HCD approach is divided into several activities which build upon each other, gradually improving the designed product(s) and allowing for an iterative process. Firstly, it involves planning the HCD process, followed by identifying and specifying the context of use by understanding who the users are, what they aim to achieve, and under what conditions they will interact with the systems. This is further followed by specifying the user requirements, developing design solutions that meet those requirements, and iteratively evaluating the design through testing and feedback to ensure the final products appropriately align with the user needs and expectations [17].

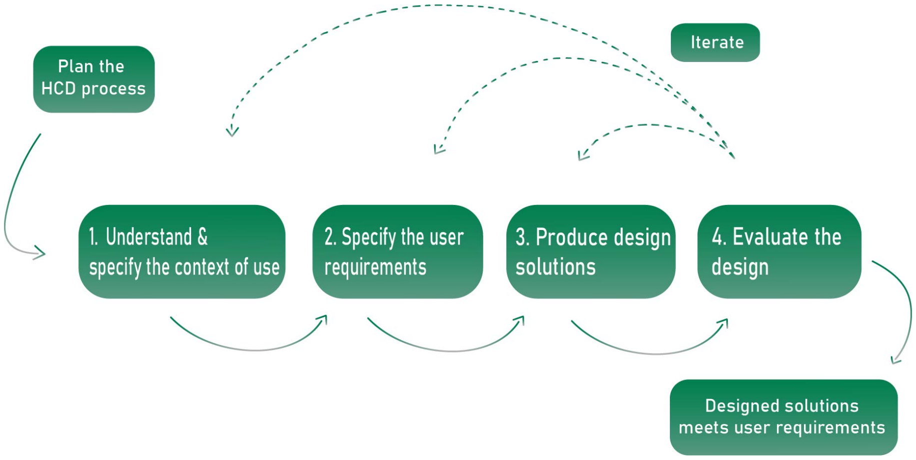

Plan the HCD process
Iterate
1. Understand & specify the context of use
2. Specify the user requirements
3. Produce design solutions
4. Evaluate the design
Designed solutions meets user requirements

Figure 3.3: Human-centered design process, adapted from [17]

3.3.2 Identifying participant groups

The goals developed for the data gathering session will indicate the types of people from whom data is to be gathered, namely called the study population [56]. To ensure relevant and meaningful feedback, participant groups were identified based on the goals of the immersive learning experiences. Participants were selected to represent typical users of the prototypes, with a focus on individuals who reflect the target audience, namely people who visit and are most likely to visit museums in the future. Further talks with the natural museum staff expressed that a wide range of the visitor demographics involves students from high schools and universities, which allowed to simplify the design focus and focus mostly on university students at the University of Agder campus in Grimstad. Additionally, the selection process ensured a balance between participants with varying levels of experience with the technologies chosen, enabling a more comprehensive evaluation.

As the study involved two distinct scenarios of use, one using VR and the other using MR, participants were divided into separate groups to avoid learning effects and potential bias in memory retention. In the first iteration, three participants tested each prototype, resulting in a total of six participants. In the second iteration, five participants were assigned to each prototype test, totaling ten participants. In total across both iterations, sixteen participants were involved in the user testing study.

Iteration	Prototype	Participants	User Test Count
Iteration 1	VR	3	Test 1
Iteration 1	MR	3	Test 2
Iteration 2	VR	5	Test 3
Iteration 2	MR	5	Test 4
	Total	**16**	**4**

Table 3.1: Participant division overview

3.3.3 Qualitative interviews

Qualitative interviews can be thought of as a 'conversation with a purpose', where it is gathered information about participant's thoughts and opinions as mentioned [56]. These can further be categorized into structured, unstructured, semi-structured or group interviews [56]. Semi-structured refers to the combination of features of structured and unstructured interviews, where usually questions and topics are planned but further questions are asked to find more relevant information. Furthermore, focus groups usually involves a small group of participants which is guided by a facilitator. The most appropriate approach to interviews depends always on what the purpose of the interview is, the questions to be addressed, and the interaction activity. Interviews can be conducted in various settings depending on the context of the study, including in-person, remotely via video, or even over the phone [56]. They may take place in controlled-environments or public environments such as on the street. Such street interviews where it is usually more flexible, can be valuable for gathering spontaneous and content-rich insights that might not emerge in more controlled environments [56]. An example can be user interviews [57], which take part in the initial phases of a HCD process. Early user interviews play a crucial role in informing the conceptual development of the prototypes. By engaging with potential users at an early stage, the study ensures that the design direction aligns with user needs and educational relevance as well as potentially identifying challenges before implementation.

As mentioned, deciding on what interview approach to follow revolves around the purpose of the study. Sometimes, interviews can range from brief and direct to more in-depth [56]. Short, focused interviews are useful for gathering quick feedback, especially when time or participant availability is limited. Despite their brevity, they can still involve meaningful insights if well structured. In contrast, in-depth interviews allow for a more comprehensive exploration of user experiences, motivations, and perceptions, often uncovering nuanced information that may not have been noticed through other methods, usually allocated after a system and/or a prototype has been tested [56].

3.3.4 Qualitative dominant mixed method approach

There are different definitions that conceptualize the term 'mixed methods'. As the term suggest, it involves incorporating different data collections methods, namely qualitative and quantitative [21]. This study incorporates a mixed method approach, specifically qualitative dominant. Qualitative data is usually in the form of numbers, or data that can easily be translated into numbers [56]. Qualitative in contrast can be in form of words and images, including descriptions and/or quotes from participants [56]. A qualitative dominant mixed method research is positioned on the qualitative end of the mixed methods continuum [21], which illustrates the rage of emphasis a study might place on qualitative versus quantitative methods. In a qualitative dominant research, methods such as interviews and observations are central, while quantitative methods like questionnaires play a supportive role, which supports why opting for a mixed method approach can have a positive influence. This way, the researchers can gain in-depth understanding, and additionally measurable evidence in form of questionnaires, allowing therefore for a more comprehensive exploration of the research topic [21] [56].

However, it is important to take into consideration that both qualitative and quantitative data collection methods can present certain challenges. While qualitative methods offer valuable insights into participant's experiences and feedback, they may however be time consuming to conduct and further analyze, being therefore subject to researcher bias [56]. Quantitative methods may on the other hand lack the depth needed to fully understand user experiences or contextual factors. As a result, it is important to balance these approaches by ensuring careful planning in the design, execution, and integration of both data types, so that that qualitative depth enriches the quantitative scope, and the overall findings remain coherent, reliable, and ultimately align with the research objectives within the study.

3.3.5 Addressing biases in research

In a research involving participants where data gathering and analysis are involved, researchers need to take into consideration bias. Bias in research refers to systematic errors that can misrepresent data collection, analysis, or interpretation, ultimately having an impact on the validity and reliability of the study's findings.

In a mixed methods research approach, bias [68] can emerge at various stages of the process, from the selection of participants to how data is gathered and interpreted. For instance, common forms of bias include selection bias, where the participants' sample does not accurately represent the target population, and further measurement bias, which results from the use of inconsistent or flawed data collection tools [68]. Additionally, observer and confirmation bias are specifically relevant regarding the researchers as the researcher's expectations can influence what is observed and how responses are interpreted [68]. Moreover, researchers also need to keep in mind participant's behaviors which can also involve bias. For example, their behavior during user testing may be influenced by their awareness of being in a study, which is a term known as the Hawthorne effect [62]. Similarly, social desirability bias [15] can lead to participants to respond in ways they believe are favorable in order to make an impression rather than providing honest feedback. Another common form of bias introduced by researchers, whether intentionally or unintentionally, is the use of suggestive wording or contextual cues that can influence how participants think, behave, or respond. This is known as the priming effect [68]. For instance, after user testing, instead of asking 'What did you like most about the experience?', a better formulation would be 'What stood out to you most during the experience?', as it could guide participants toward only positive responses, instead of encouraging open-ended reflection without implying a positive or negative judgment.

3.4 Usability testing

Experiments and user tests are typically structured to study participant behavior, including what tasks they perform, when they perform them, and for how long. The goal is to minimize external distractions or environmental factors, such as background noise or interruptions, that could potentially influence the outcome of the results [56]. This approach is known as usability testing, where a user-centered evaluation method is used to assess how effectively, efficiently, and satisfactorily users can interact with a system. The primary goal is to determine whether the designed system is usable for the people for whom it was designed [56]. It involves observing real users as they attempt to complete dedicated and specific tasks, with the goal of identifying potential usability issues, understanding user behavior, and gathering feedback to inform iterative design improvements. A usability test is typically performed in a controlled-setting such as in a tightly controlled laboratory, where activities include interviews, observations and questionnaires [56].

To test and evaluate the designed prototypes, a usability testing for this study was conducted within two different controlled environments. The usability testing was conducted with sixteen participants over four testing sessions as part of an iterative HCD process. Firstly, two tests were conducted with six participants, three for each designed prototype. Thereafter, changes were made and implemented based on feedback gathered and further tested in a second round on ten new participants, five for each prototype. An interview guide shown in Appendix B served as a foundation to conduct the usability testing. During the recruiting phase, participants were approached both at the university and at the museum, and asked to participate. Participants were recruited through a combination of convenience and purposive sampling [56]. University students were mainly selected based on accessibility and availability, while efforts were made to include individuals from the museum setting to ensure contextual relevance. Additionally, participants were intentionally chosen to reflect diversity in age, gender, and familiarity with the technology, providing therefore a broad range of perspectives.

3.4.1 Pre-test interview

The usability testing began firstly with a six question pre-test interview aimed at understanding the participants' background and familiarity with museums, technology, and immersive system, as well as their learning preferences and attitudes toward interactive exhibits. Pre-test interviews are typically brief and serve to put participants at ease while familiarizing them with the controlled testing environment. The goal is to create a comfortable atmosphere that encourages open, honest engagement during the usability session.

3.4.2 Observations

Thereafter, participants were given the Meta Quest 3 and asked to test one of the prototypes. During this phase, observations were conducted to capture real-time user behavior, interactions patterns, and non-verbal cues that might not be expressed during interviews, or questionnaires [56]. Digital notes were taken along the observation phase while participants performed given user tasks. Areas that were looked at during the observation included eventual moments of hesitation or confusion, task completion success, signs of frustration, requests for help, critical errors, and unexpected interactions. These focus points served as prompts to better understand user experience without influencing or interrupting participant behavior. Additionally, participants were reminded to think aloud [47] while using the prototype, verbalizing their thoughts, intentions, and reactions while performing tasks. This technique provided a valuable insight into the reasoning behind certain user actions and helped reveal areas of confusion or uncertainty that might not have been evident through behavior alone.

3.4.3 Questionnaires

After the observation phase ended, participants were asked to complete two post-test questionnaires designed to collect structured, quantitative data related to their experience with the prototype, providing therefore statistical data [56]. The questionnaires aimed to evaluate key dimensions of the study, including the participant's perceived presence, engagement, memory retention and ease of interaction regarding the modalities incorporated in the tested prototype. Questionnaires offer a faster and more scalable method of data collection as opposed to qualitative methods, as they can be completed independently without the researchers being present. However, this also means that the questions must be clearly structured, neutrally worded, and well-interpreted to avoid misunderstandings or response bias [56].

To ensure relevance and accuracy, each questionnaire had to be adapted according to the prototype to be tested. While the format and amount of questions were similar, the VR questionnaire included questions tailored to controller-based interaction and the stationary nature of the experience, while the MR questionnaire focused on physical movement, hand tracking, and spatial interaction. Both versions used a Liker-scale format, a rating scale often used in questionnaires in order to measure participants' perceived interaction, how engaged they felt, and how well they recalled or understood the learning content by asking them to indicate their level of agreement on a fixed scale, typically ranging from 'strongly disagree' to 'strongly agree'. These structured responses provided a quantitative complement to the qualitative insights gathered through interviews and observations, enabling cross-comparison between the two prototypes and strengthening the overall study analysis.

The structure and content of the questionnaires were inspired by validated instruments used in immersive research, a paper by Tcha-Tokey et al. [70] which focuses on measuring user experience in immersive virtual environments. Presence and engagement related questions were inspired and adapted according to the Presence Questionnaire by Witmer and Singer [85]. Unlike established instruments for measuring presence or engagement, there is no standardized tool for assessing memory retention in immersive experiences. Therefore, questions related to recall of information were inspired by Mayer's Cognitive Theory of Multimedia Learning [33], which emphasizes how design impacts memory and learning.

System usability scale (SUS)

In addition to the adapted post-test questionnaire, the System Usability Scale (SUS) [29], was used to evaluate the overall usability of both prototypes. SUS is a widely adopted, standardized instrument consisting of ten items rated on a five-point Likert-scale, designed to capture users' perceptions of system usability in terms of efficiency, effectiveness, and satisfaction [29]. One of the key strengths of SUS is its universality as it can be applied across a wide range of technologies and interfaces, regardless of the specific platform or system type. This form of questionnaire made it particularly suitable for comparing the usability of both prototype approaches used in the study.

3.4.4 Post-test interview

The final phase of the usability testing consisted of an in-depth semi-structured post-test interview to understand and gather deeper qualitative insights into the participants' experiences and behaviors throughout the experience. This allowed participants to reflect on certain aspects of the system such as interaction comfort, how engaging the system was, how involved they felt and also their perceived learning value. In addition, a short oral recall task consisting of eight questions was included to assess memory retention by asking participants to recall specific procedures and details encountered during the experiences. These questions would verify if the intended learning outcomes were met by the end of the experience. As with questionnaires, these post-test interviews were also adapted to the specific prototype approach that each participant tested, ensuring that the questions were relevant to the interaction modality and context of use. For instance, MR participants were further asked about their experiences with hand tracking and physical movement, while VR participants reflected on controller-based interaction and stationary use.

3.5 Qualitative data analysis

Once participants' testing sessions are completed, sets of raw qualitative data are collected and further prepared for analysis. Initial steps in qualitative data analysis involve gaining an overall impression of the collected data, and start looking for features, topics, observations or any specific type of patterns [56]. This identification helps researchers get a good overview of the data and makes it easier to start organizing information into useful categories for analysis. There are several approaches to analyzing qualitative data, one being thematic analysis [56] [9].

3.5.1 Thematic analysis

A thematic analysis approach was utilized in the study to analyze the gathered qualitative data. What makes this approach so effective is its flexible method for identifying, analyzing, and identifying valuable insights, and potential patterns from gathered data [9]. One of the strengths of this approach is its adaptability, which can be adapted to suit the specific goals, context, and depth of the researcher's study, making it ideal for experiential research involving varied user feedback [9]. The process involves systematically coding the data and grouping similar codes into generic themes and eventual sub-themes that reflect key aspects of the participants' experiences and behaviors [9]. A thematic analysis involves 6 phases [9]: Familiarize with the data, code the data, generate initial themes and sub-themes, review the themes and sub-themes, define and name the themes and finally report the findings. During testing sessions, observational and interview notes were digitally taken, either in the form of concise bullet points or in short descriptive statements. This approach allowed for efficient coding and pattern recognition, enabling the identification of themes and sub-themes across both iteration analysis phases. The full thematic analysis from both iterations can be seen in Appendix H.

Chapter 4

Design & Development

This chapter provides an overview of the design and development process of the virtual and mixed reality herbarium prototypes. It outlines and conceptualizes both prototypes, its technical development and what it includes, a list of applied educational design principles guidelines, inspirations behind the project's idea and how the collaboration with the natural museum prolonged through the development process, interactive functionality and technical integration, hardware and software utilized, scripts, modeling phase as well as assets utilized, and lastly the challenges discovered throughout process and their solutions. A link showing two short video demos of the prototypes is presented in Appendix A.

4.1 Idea & inspiration

During the course MM-505 Virtual and Augmented Reality [76] in the master's program Multimedia Educational Technology, the researchers developed a mixed reality prototype titled ManCave [59] as part of an exam project, which became a key inspiration for this master thesis. Utilizing the Meta Quest 3's [35] spatial scanning capabilities, the application digitized a real room and overlaid it with interactive 3D models, allowing users to physically navigate and engage with virtual objects using hand tracking or controllers, such as slot machines, a cassette player, and a pool table. Interestingly, during user testing, participants who had seen the real room beforehand consistently avoided walking through the virtual pool table, treating it as if it were physically present, while interacting naturally with the slot machines that rested on actual tables. Even after being told mid-experience that the pool table wasn't real, users who attempted to walk through it experienced disorientation and dizziness, indicating a strong sense of presence where cognitive and perceptual boundaries between real and virtual had blurred. These reactions, along with other findings, motivated the researchers to explore how the immersive realism achieved in ManCave could be applied in educational settings, highlighting the potential of mixed reality as a powerful tool for learning.

4.1.1 Collaboration with the natural museum

Throughout the design and development process, the project was carried out in close collaboration with the natural history museum in Kristiansand, which initially proposed the idea of creating an immersive educational experience based on the herbarium, which is located in a closed department at the museum. Monthly meetings were held to present the development process and gather feedback from the museum, ensuring alignment with the museum's educational goals. This idea of developing two prototypes, which will be further explained in the next sub section, was proposed to the museum to allow future flexibility should a dedicated space for the mixed reality approach, however for the time being, the museum focused more on the development of the virtual reality prototype.

Furthermore, the museum provided a document outlining key learning outcomes and scenario descriptions of each individual procedure, which formed the foundation for the interaction design. Therefore, to ensure accuracy and realism, additional meetings were arranged to observe museum employees that worked at the herbarium perform the actual herbarium procedures physically, allowing for the observation to replicate accurately in the immersive environments. While there were several scenarios of procedures initially presented, time constraints limited the implementation to the most essential ones that the researchers felt were critical for users to understand the core procedures while still meeting the described intended learning outcomes.

4.1.2 Inspiration for developing two prototypes

The initial intention for this project was to focus exclusively on the development of a MR prototype. However, during the first meeting with the staff of the natural museum in Kristiansand, it became clear that their interest leaned more heavily toward a VR solution. This was primarily due to spatial limitations within the museum, which made it impractical to implement a room-scale MR experience for the time being. The physical layout of the museum could not accommodate the movement and spatial scanning requirements necessary for a fully functional MR application.

This divergence between the original project goals and the museum's expectations presented a significant design and logistical challenge. After careful reflection and consultation with academic supervisors, the project team decided to develop two separate prototypes, one in VR and one in MR, and to investigate how each approach can facilitate learning in different ways while providing an engaging and memorable experience.

This pivot not only addressed the external constraints posed by the museum environment, but also introduced an opportunity for comparative research. The development of two parallel prototypes allowed for an exploratory study of the differences in user experience, interaction, and perceived learning between virtual and mixed reality formats.

4.2 Educational design principles & guidelines

When designing the two prototypes, it was essential to ground the development process in established educational design principles, particularly relevant to immersive learning environments such as virtual and mixed reality. Therefore, the researchers referred to the book Embodied Learning in a Digital World by Johnson-Glenberg[22], which presents a comprehensive set of guidelines for educational design in immersive digital contexts.

This framework proved highly relevant and was used as a guiding reference throughout the design process. The team reviewed the full list of principles and identified those most applicable to the educational objectives and technical constraints of the VR and MR herbarium prototypes. Several of these were implemented intentionally, serving as foundational elements in both interaction design and content presentation. The following subsections describe each selected guideline, along with specific examples of where they were applied across the two prototypes.

- **1 - Assume every learner is a VR beginner**

  The MR prototype begins with a dedicated tutorial area designed to introduce users to interaction types, UI elements, and key objects. It uses a multimodal approach, combining text, video, and hands-on practice with test objects, promoting active learning and fluency from the start. The VR prototype offers a simpler onboarding screen displaying controller functions, supported by voice instructions and animated guiding circles to direct user attention and aid orientation.

- **2 - Introduce User Interface (UI) components judiciously, fewer is better**

  The MR prototype features a single persistent UI panel in the top left corner, showing a brief task description and a menu icon to access additional guidance. This minimalist design was added in response to user feedback, aiming to reduce cognitive load while maintaining ongoing task support. Beyond this element, both prototypes use only a few additional UI components, strategically placed informational hub screens and interaction based UI indicators. These context sensitive cues, such as icons or animations, help users understand how to interact with specific objects without overwhelming the visual field.

- **3 - Scaffold—introduce cognitive steps one at a time**

  Both prototypes applied scaffolding principles by gradually increasing cognitive complexity. At the start of the MR prototype, a tutorial space guided users through core interaction types like poke, grab, and pinch, using a combination of text, video, and hands-on practice with test objects. This familiarized users with essential mechanics before introducing more advanced tasks. To reinforce learning, the same UI icons used during the tutorial were consistently attached to interactive objects throughout the experience, serving as visual reminders. Task progression was deliberately structured. Early tasks focused on basic interactions like operating the elevator or equipping gear. Only after users mastered these fundamentals were more complex tasks introduced—such as operating the plant presser, which combined multiple interaction types. Contextual UI cues supported each step, allowing users to build on prior knowledge and engage with increasing task complexity in a manageable, guided way.

- **4 - Co–design with teachers**

  As outlined in Section 4.1.1, the development process was closely guided by continuous collaboration with staff from the Natural History Museum in Kristiansand, particularly those responsible for the herbarium. The museum not only initiated the project idea but also played an active role throughout development. Monthly meetings were held to share progress, present prototypes, and gather feedback, ensuring that both learning objectives and procedural accuracy aligned with the museum's educational goals. The museum also provided scenario descriptions and key learning outcomes, which shaped the interaction and content design of both VR and MR prototypes. To support authentic simulation, the research team conducted on-site observations of herbarium staff performing real world tasks such as drying, pressing, DNA gathering and archiving specimens. These insights informed the design of realistic workflows and ensured that the virtual experience remained pedagogically and procedurally relevant.

- **5 - Use guided exploration**

  Both the VR and MR prototypes integrated the principle of guided exploration. While some degree of initial free exploration was allowed to foster curiosity and spatial orientation.

  In the VR prototype, users were initially placed in a spacious reception area, where they were free to look around and explore. However, once they chose to proceed beyond the reception, the experience shifts to a more structured format. Learners are guided along a structured path using a combination of animated green circles to indicate navigation points, audio cues, and interactive info screens with both text and voice-over narration. To further reinforce the intended learning sequence, access to areas outside the current task zone was restricted, ensuring users remained focused on the designated activity and did not wander into unrelated parts of the environment.

  In the MR prototype, users can physically move around the real-world-mapped environment from the outset. However, structured learning was immediately introduced through a task system, beginning with the first task to use the elevator and travel to the wardrobe floor. This first mission introduced the player to the task completion feedback system through a completion chime, immediately reinforcing progression. Throughout the experience, users were guided using static notifications displayed in the top-right corner of the view, which showed the current mission. The combination of audio feedback, text instructions, and context-sensitive UI indicators provided a consistent and supportive learning framework while still giving a sense of autonomy.

- **6 - Minimize text reading**

  While the info screen UIs contained textual content to convey important information about the herbarium processes, users were consistently provided with the option to listen to voice-over narration instead of reading.

  In addition, the prototypes relied on animated icons and visual cues to represent core interaction types such as grab, poke, and pinch. These informative graphics helped communicate interaction affordances more intuitively, aligning with the recommendation to favor visuals and mini-animations over written instructions whenever possible.

- **7 - Build for low stakes errors early on**

  An example of this can be seen during the DNA testing procedure, where users must select a suitable piece of a dried plant for analysis. Several options are presented, but only two of them are considered valid for DNA extraction.

  If a user selects an incorrect piece, the system responds non-punitively by displaying a red circular visual cue, signaling that the selection is unsuitable for testing. No progress is lost, and users are free to try again until they make a correct selection. When the user successfully selects an appropriate piece, a green circle appears to confirm the correct choice and signal task progression.

  Another example can be seen when users attempt to start the drying cabinet without having placed a plant inside. Instead of triggering an error or blocking progression without explanation, the system displays a text prompt informing the user that a plant presser must be inserted before the cabinet can be activated.

- **8 - Playtest often with both novices and end-users**

  The development process followed the guideline of frequent playtesting with target users rather than relying solely on developer feedback. As detailed in Section 3.4 Usability testing, multiple rounds of usability testing were conducted with both university students and museum visitors across varying levels of technological familiarity. This iterative approach enabled the researchers to collect practical insights from real end-users and make informed adjustments to both the VR and MR prototypes.

- **9 - Give players unobtrusive, immediate, and actionable feedback**

  Both prototypes incorporate immediate and unobtrusive feedback mechanisms to support cognitive integration without disrupting user immersion. For example, upon completing a task, users hear a mission-completion chime, and in the MR prototype, the persistent UI in the upper right corner automatically updates to reflect the next objective. Additionally, incorrect actions—such as selecting an unsuitable plant sample for DNA testing—trigger subtle but clear visual cues, such as a red circle indicator, allowing users to try again without penalty, thus avoiding negative reinforcement.

Further, buttons across both prototypes provide immediate audio and visual feedback, such as a color shift to green when successfully pressed, enhancing clarity and reinforcing correct interactions. The plant presser utilized a stepwise UI guidance system through animated icons: initially showing a pinch icon to signal the required gesture, then changing to a rotation icon once the user engaged with the lock, and finally displaying an animated padlock opening icon once the lock was correctly rotated, effectively guiding users through the multi-step interaction. Similarly, when tweezers were grabbed, an animated pinch icon appeared above them, reinforcing the expected interaction pattern and supporting gesture learning. These layered feedback cues contributed to a smoother and more intuitive learning experience across both prototypes.

- **10 - Design in opportunities for reflection (it should not be all action and twitch!)**

  In both prototypes, opportunities for reflection were embedded through intentional design choices that allow users to engage at their own pace. While the next task is presented immediately after the previous one, there are no time constraints or countdown timers pressuring the user to continue. This design enables users to pause, consider their actions, and reflect on the information presented before progressing. Info screens and accompanying voice-overs also provide moments of reduced activity, encouraging thoughtful engagement with the material.

  An exception to this pacing is the final mission, in which an alarm sound is triggered and the user is prompted to locate the temperature room. Although this event introduces a sense of urgency, it does not impose a strict time limit or countdown. Users can still complete the task at their own pace, ensuring that even under simulated stress, the learning environment remains supportive rather than overwhelming.

- **11 - Use the hand controls to encourage the learners to be "active"**

  This principle emphasizes the importance of physical engagement during learning. The VR and MR prototypes were designed to leverage a variety of interaction modalities that required users to actively manipulate digital content using their hands or controllers. For instance, users grabbed objects such as the plant presser, used poke interactions on buttons, and pinched their fingers to operate the lock mechanism on the presser. These tasks were not passive, but they demanded kinesthetic involvement, making users physically engaged in the learning experience. The goal was to mirror real-world gestures to strengthen embodiment and enhance memory retention.

In the MR prototype, hand tracking further elevated this principle by allowing users to interact without controllers. Grabbing for example the spray bottle and squeezing the index finger to disinfect the tweezers involved actual physical motion that closely resembled real-life behavior.

- **12 - How can a body-based metaphor be applied?**

  While the previous principle focused on activity for engagement, this principle centers around the meaningfulness of those actions. It emphasizes designing interactions where body movements represent or reinforce abstract cognitive concepts. In both prototypes, this was applied in several places. For example, the action of pinching the tweezers to extract a plant sample was not just a functional gesture, it metaphorically mirrors the scientific process of carefully selecting material for DNA testing. Similarly, turning the lock on the plant presser reflected the real world act of sealing something securely, a gesture loaded with representational meaning.

  Additionally, spraying disinfectant using the bottle was not a generic action, but one that mimicked the exact physical routine of sanitizing in a lab setting. These movements are congruent with the intended educational context, grounding abstract procedural knowledge in concrete bodily experience.

- **13 - Congruency**

  Many of the interactions designed in the prototypes adhered to the principle of congruency by ensuring that user actions closely mirrored their real-world equivalents. As previously described, elements such as the spray bottle, tweezers, the presser's locking mechanism, and the physical action of lifting the presser lid were all implemented with gestures and motions that reflect how such tools are used in reality. By mapping virtual interactions to familiar motor patterns, the experience becomes more intuitive, reducing cognitive friction and reinforcing the connection between physical action and conceptual understanding. This alignment between gesture and function enhances the learning process by leveraging embodied cognition and minimizing the need for abstract control schemes.

- **14 - Actions strengthen motor circuits and memory traces**

  The prototypes were intentionally designed to require physical actions that mirror real world procedures, thereby activating the user's motor system during tasks. As highlighted in earlier principles, interactions such as pinching to operate the presser lock, grabbing and rotating the presser lid, or manipulating the tweezers to extract plant samples engage users in embodied tasks. These actions do more than just simulate procedures, they also help in strengthening memory traces by coupling motor engagement with conceptual understanding.

- **15 - Ownership and agency**

  While the previously mentioned principle of guided exploration emphasizes structured learning paths to reduce cognitive overload, it does not necessarily conflict with fostering agency. Instead, the two principles can be seen as complementary. In the two prototypes, users are guided through structured tasks using visual and auditory cues, such as mission chimes, green navigation markers, and contextual UI elements. However, within this structured path, users retain control over how they interact with the environment. They can decide when to engage with tasks, which hand to use for grabbing objects, and how much time they want to spend exploring before moving on.

4.3 The immersive experiences use case - Herbarium

The use case for the immersive prototypes was based on a real-world herbarium located at the natural history museum in Kristiansand [46]. A herbarium is a scientific collection of preserved plant specimens that are systematically cataloged and stored for the purpose of research, education and conservation. These specimens, which include dried, pressed plants mounted on 'sheets', are fundamental for studying plant biodiversity, taxonomy, and ecological history [46]. There are over 85.000 dried pants, where most of them are from Agder. The oldest coatings are from around the 1830s being therefore over 190 years old [46]. The herbarium is restricted to researchers due to preservation and environmental control requirements, making it inaccessible to the general public.

As mentioned, the immersive environment was intended to reflect the physical layout and atmosphere of the real-world herbarium at the museum. However, during on-site visits, it became evident that the actual space was relatively small and lacked modern features typically associated with more advanced research facilities. To address this, the researchers decided to expand and modernize the virtual environment slightly, drawing inspiration from visual references of herbariums around the world [82]. This allowed for a more spacious and engaging user experience while still maintaining the educational intent and scientific authenticity of the setting. Below is an illustration of the actual herbarium laboratory and the improvised version by the researchers. Additionally, for the purpose of the VR prototype, the reception of the museum was also modeled reflecting the exact layout.

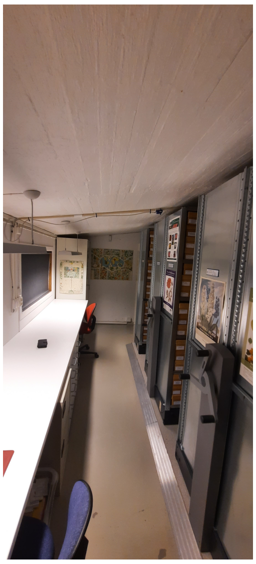


Figure 4.1: Real-world herbarium lab at the museum

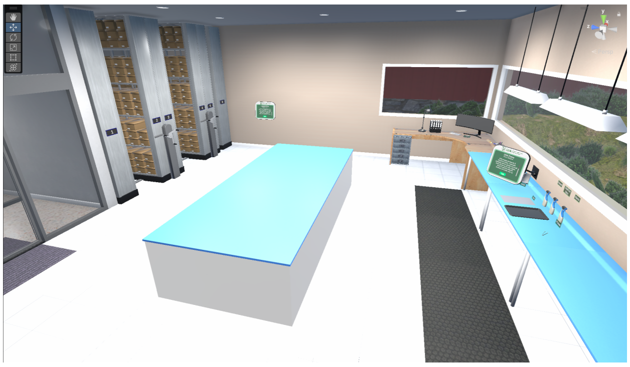


Figure 4.2: Improvised version of the herbarium lab in the immersive experience (VR Prototype specifically)

4.3.1 Conceptualizing the immersive experiences & approaches

The prototypes are immersive experiences where users virtually explores the herbarium: one fully virtual and the other in mixed reality. Within these environments, users learn and engage with various procedures and scenarios based on real tasks performed at the herbarium. Through active exploration, users can physically interact with elements within each scenarios' tasks, namely equipping appropriate protective clothing to prevent contamination, pressing and preparing plant specimens, extracting DNA samples, and managing archival procedures including temperature adjustment. Interactive information screens are placed throughout the environment to further guide and inform the user which users can read or listen to. These screens provide detailed theoretical explanations for each scenario with the goal of enhancing the educational experience. The experiences begin in the museum's reception area, designed to introduce users to the controls and provide context for the simulation. Users assumed the role of a researcher at the museum, with the objective of locating the herbarium and completing diverse tasks. Along the way, users engaged with interactive elements such as automatic doors, manually operated doors, and elevators activated by button presses, enhancing the sense of agency and realism within the experiences.

Both prototype approaches revolved around the same concepts and procedures, meaning that each scenario that is included in one prototype is also included in the other. This was to ensure consistency in both prototypes. The only differences lied in the prototype approaches, one being VR and the other being MR and their interaction modalities. The experiences consisted of two different scenes with diverse areas the user could explore: the reception and the herbarium laboratory which consisted of the entrance/wardrobe, main laboratory, pressing room and generator room. A storyboard, shown in Appendix D, was created during the initial phases of the human-centered-design [17] approach to illustrate how the different areas of the environment were planned to look like as well as some design considerations and concepts of the procedures that the users would interact with.

Virtual reality prototype

In the VR prototype, users were fully immersed in a complete virtual environment while remaining in stationary position, either standing or seated, and interacting through handheld controllers. Navigation was achieved using teleportation, allowing users to move between areas of the environment and using the controller inputs to trigger either grabbing or poking gestures. These two gestures were intentionally chosen to avoid overwhelming the user with a wide range of interaction options or complex input combinations.

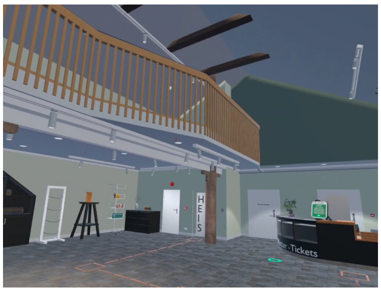


Figure 4.3: Museum entrance

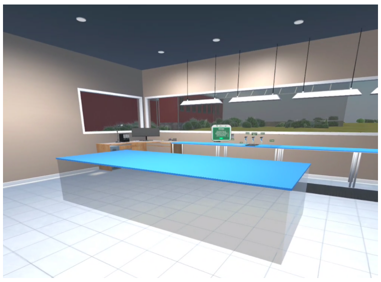


Figure 4.4: Herbarium main lab

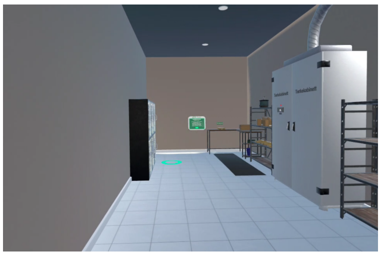


Figure 4.5: Pressing room area

Mixed reality prototype

In the MR prototype users were immersed in a mixed reality environment using pass-through where virtual content was overlaid onto a real environment. These areas needed to be sufficiently spacious to accommodate both user movement and the placement of virtual objects within the environment. Unlike the VR prototype, users could physically walk around the spatial scanned area and utilized hand tracking as a way of interaction with the objects. These interactions were achieved through natural hand gestures such as grabbing, pinching, and poking.

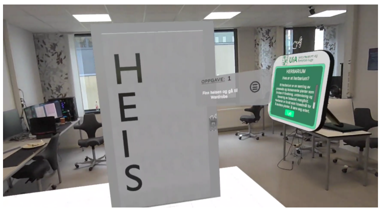


Figure 4.6: Museum entrance in MR

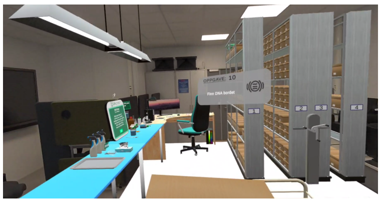


Figure 4.7: Herbarium main lab in MR

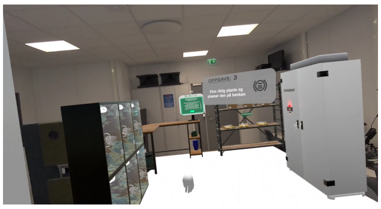


Figure 4.8: Pressing room area in MR

4.3.2 List of scenarios/procedures

The natural museum provided a document in the early stages of the project outlining each specific scenario procedure. Due to time constraints, the most essential were taken into consideration into the design and development process. A text script of the info screens learned in the prototypes can be seen in Appendix P

- Herbarium conceptualization (Understand about the herbarium in the reception area)
- Contamination measurements and safety (Equipping required clothes before entering the lab)
- Conservation (Pressing and preparing a specimen)
- DNA test procedure
- Storage of a specimen
- Temperature role and preservation measurements

4.3.3 Intended learning outcomes

The described intended learning outcomes were initially based on the museum's intentions and further adapted to Bloom's taxonomy [3] of effective educational objectives.

- The learner should be able to define what an herbarium is
- The learner should explain the importance of preservation techniques in an herbarium, including how to prevent contamination and maintain plant specimens
- The learner should demonstrate how to properly handle, mount, and press plant specimens following herbarium guidelines
- The learner should be able to recall, recognize and relate concepts learned in the immersive experiences to the real world
- The learner should distinguish between different objects and tools used in an herbarium and explain their role

4.4 Tools & Software used

The development of the VR and MR prototypes required a combination of modeling, programming, and integration tools. The selected software platforms were chosen based on prior experience, flexibility, and compatibility with the Meta Quest 3 headset [35]. The core tools used in this project were Blender [11], Unity[71], Meta XR All-in-One SDK [37], and Visual Studio Code[40].

4.4.1 Blender

Blender [11] is an open source 3D creation software used for modeling, sculpting, texturing, and animation. It is widely recognized for its robust capabilities and active community support. In this project, Blender was used to create custom 3D assets where suitable models were unavailable or required optimization. Its non-destructive workflow, support for PBR (physically based rendering) materials, and compatibility with Unity made it an ideal choice for building lightweight, optimized models tailored for real-time rendering on standalone devices like the Quest 3.

4.4.2 Unity

Unity[71] is a cross-platform real-time game engine that offers powerful tools for developing interactive 3D content, particularly for VR and MR applications. Unity was selected for this project due to its strong support for XR development, extensive documentation, and native integration with Meta's XR hardware. The engine allows developers to implement physics, interaction systems, and complex animations while maintaining real-time performance across devices. Its component-based architecture and visual editor provided an efficient workflow for iterative prototyping and testing. For the development of both prototypes, two distinct unity projects were created dedicated to each prototype, allowing for an organized and structured technical workspace.

4.4.3 Meta XR All-in-One SDK

The Meta XR All-in-One SDK [37], provided by Meta, is a unified development toolkit designed to support the full spectrum of XR capabilities on Meta Quest devices. By integrating this SDK into Unity, the project was able to leverage the advanced features of the Quest 3, such as mixed reality passthrough, spatial awareness, and gesture-based input. The SDK's built-in components for grab, poke, ray, and socket interactions enabled implementation of intuitive hand and controller-based systems across both prototypes, making it a important element in development of the two prototypes.

4.4.4 Visual Studio Code

Visual[40] Studio Code (VS Code) served as the primary code editor throughout the development process. Lightweight yet powerful, VS Code offers support for C# Unity's primary scripting language—alongside features such as IntelliSense [39], and debugging tools. Its ease of use and customization made it an efficient environment for scripting interactive logic and debugging application behavior during playtesting.

4.5 Hardware - Meta Quest 3

The Meta Quest 3[35], released in 2023, was used as the primary hardware for both VR and MR prototypes. As a standalone headset, it requires no external sensors or PC connection. Powered by a Snapdragon XR2 Gen 2 processor and 8 GB of RAM, it offers significantly better performance than earlier models like the Quest 1 and 2[81] [80].

Key improvements include high-resolution pancake lenses (2064 × 2208 per eye), a refresh rate up to 120 Hz, and a wider 110° field of view—enhancing clarity, immersion, and user comfort. Full-color pass-through via dual RGB cameras, inside-out tracking, hand tracking, and controller support further enable seamless transitions between VR and MR. These advanced capabilities made the Quest 3 an ideal platform for delivering immersive educational experiences in this project.

4.6 Human-centered design approach in development

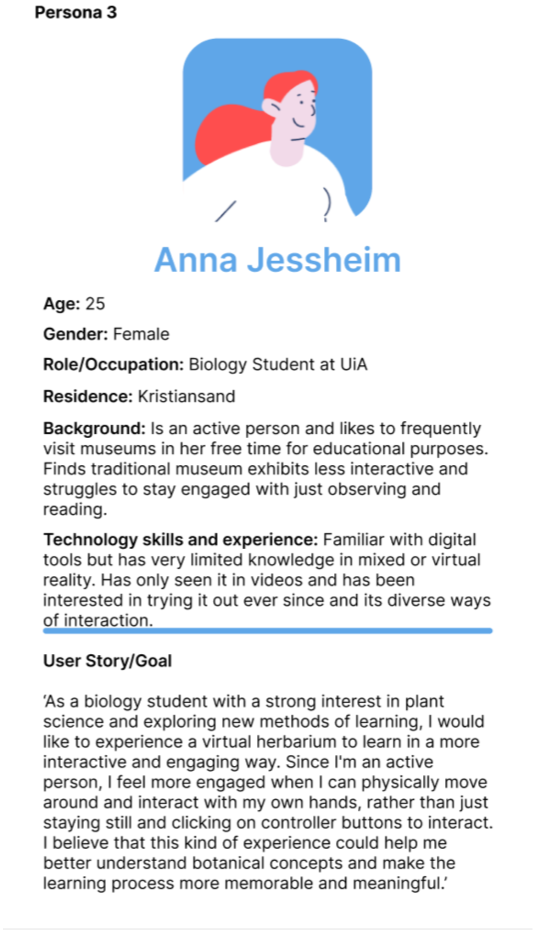
The development of the immersive experience prototypes was guided using a HCD approach, which followed four foundational and iterative components: understanding and specifying the context of use, specifying user requirements, producing design solutions and evaluating the design according to the defined requirements. It emphasizes the importance of designing systems with a focus on human needs, ergonomics, affordances, and the context of use [17]. This iterative approach allowed the researchers to continuously refine the prototypes based on gathered feedback, ensuring that each design decision aligned with user's needs, expectations and the educational goals of the study.

Traditionally, a HCD process is planned prior to development. However, while the researchers had some prior experience with the Meta Quest 3, Unity and the Meta XR All-in-One SDK, the development phase required ongoing exploration and adaptation, and began therefore in parallel with planning the HCD process, deviating from the traditional HCD model. Initial steps within this phase meant understanding the capabilities of the technology and finding out what could feasibly be achieved within project's time constraints, scope and the museum's specific requirements. These considerations had to be addressed alongside the project's research. As a result, the researchers adopted an ambitious collaborative strategy by pursuing two distinct development approaches for the immersive use case presented by the museum, one in VR and one in MR.

4.6.1 Understanding and specifying context of use

To understand and specify the context of use, several design activity outputs were conducted. The goal during this phase is to identify who the users are, what tasks they are expected to perform, and the environment(s) in which the solutions would be used. Alongside, it was as important to research and explore similar systems in recent literature studies in order to find and address potential limitations. Furthermore, other early activity outputs included a PACT (People, activity, context and technology) analysis which served as a foundational method for organizing and specifying insights about the users, the nature of their interactions, the conditions and/or environments under which the system would be used, as well as the technologies involved. This analysis framework laid the foundation for future design choices and helped establish a clear understanding of the challenges and opportunities within the project's scope. The full PACT analysis can be seen in Appendix F.

Moreover, using the PACT analysis as a foundational element, personas [56] were designed to represent typical users of the prototypes, detailing key user characteristics, goals, needs, technological familiarity and potential challenges. Although personas are fictional research-informed characters, they represent the target group and ensure that the prototypes address realistic user expectations and behaviors. All designed personas can be seen in Appendix C .



Persona 3

Anna Jessheim

Age: 25

Gender: Female

Role/Occupation: Biology Student at UiA

Residence: Kristiansand

Background: Is an active person and likes to frequently visit museums in her free time for educational purposes. Finds traditional museum exhibits less interactive and struggles to stay engaged with just observing and reading.

Technology skills and experience: Familiar with digital tools but has very limited knowledge in mixed or virtual reality. Has only seen it in videos and has been interested in trying it out ever since and its diverse ways of interaction.

User Story/Goal

'As a biology student with a strong interest in plant science and exploring new methods of learning, I would like to experience a virtual herbarium to learn in a more interactive and engaging way. Since I'm an active person, I feel more engaged when I can physically move around and interact with my own hands, rather than just staying still and clicking on controller buttons to interact. I believe that this kind of experience could help me better understand botanical concepts and make the learning process more memorable and meaningful.'

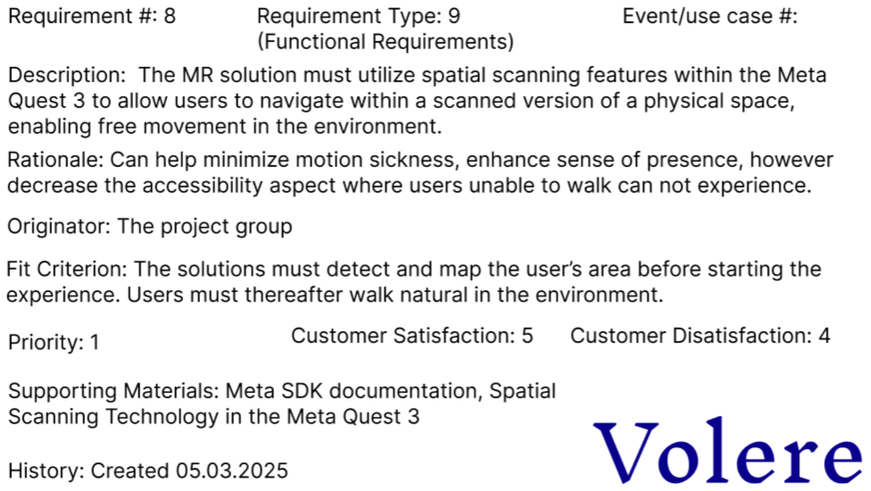
Figure 4.9: Example of a persona

To further validate the context of use and inform the development of user requirements, user interviews were conducted with six individuals at the natural museum. This early method was chosen to have an overview and get an idea of potential users. These short interviews provided valuable insights into how potential users perceive museum experiences, their learning preferences, their interest in interactive technologies, and their familiarity with immersive systems. The participants represented a mix variety of ages, genders, educational backgrounds (including students and non-students), technical experience, and learning interests, which provided valuable insights and a diverse range of perspectives. The feedback gathered from these early user interview sessions helped strengthen the understanding of the intended user group, while also helping to identify user expectations that might not have been captured through internal planning alone. The summarized and translated user interviews can be seen in Appendix N. Addressing these contextual aspects early in the design process ensures that design decisions are grounded in real-world environments and effectively aligned with user needs and requirements from the beginning.

4.6.2 Specifying user requirements

The next step in the HCD involves specifying the user requirements [56], serving as a foundation for guiding design decisions and system functionality. This process translates the insights gathered from the contextual analysis into concrete and specific actionable requirements that reflect what the system should do and how it should function, refereed to as the functional requirements, and further how well the system should perform, refereed to as the non-functional requirements.

To address this, functional and non-functional requirements were documented and organized using the Volere Requirements specification template [55] which provided a comprehensive structured format criterion previously informed by earlier design activities from the contextual phase, for instance the PACT, personas and user interviews. Due to pursuing two distinct prototype interaction approaches, some requirements had to be adapted and specified for each specific prototype. A full list of the requirements can be seen in Appendix G.



Requirement #: 8
Requirement Type: 9 (Functional Requirements)
Event/use case #:

Description: The MR solution must utilize spatial scanning features within the Meta Quest 3 to allow users to navigate within a scanned version of a physical space, enabling free movement in the environment.

Rationale: Can help minimize motion sickness, enhance sense of presence, however decrease the accessibility aspect where users unable to walk can not experience.

Originator: The project group

Fit Criterion: The solutions must detect and map the user's area before starting the experience. Users must thereafter walk natural in the environment.

Priority: 1
Customer Satisfaction: 5
Customer Disatisfaction: 4

Supporting Materials: Meta SDK documentation, Spatial Scanning Technology in the Meta Quest 3

History: Created 05.03.2025

Figure 4.10: Example of a functional requirement

4.6.3 Producing design solutions

Initial discussions and meetings with the natural museum marked the starting point for the design of the prototypes. The museum's primary interest was in the VR approach, particularly due to the fact of being the desired approach to integrate in the museum as a public exhibit. While the researchers also needed to explore a MR approach for the purposes of the study, the VR concept remained the focal point from the museum's perspective. As a result, design decisions made in collaboration with the museum were primarily based on the VR prototype and later adapted and translated into the MR version to ensure consistency across both experiences. As previously mentioned, both prototypes followed the same core use case and educational scenario, with the main distinction lying in the interaction modalities and locomotion methods as well as one being fully virtual and the other being mixed reality. The development of each prototype was informed by the contextual understanding and user requirements established in the earlier stages of the human-centered design process.

The initial development phase focused on 3D modeling of the virtual environments in Blender [11]. Once modeled, the assets were imported into Unity, where two separate projects were developed in parallel, one for the VR prototype and one for the MR prototype. Each began with a basic scene setup, with early efforts concentrated on defining user interaction and movement using the Oculus Integration SDK. These foundational setups gradually evolved to include the logic and structure for the multiple educational scenarios that the user would navigate and perform. Moreover, to ensure a stable and guided user experience, particular emphasis was placed on full-proofing the interactions, preventing users from performing unintended actions that could disrupt the flow or functionality of the experience. A linear progression structure was implemented across both prototypes, requiring users to complete specific tasks in sequence before advancing. This structure was essential for maintaining narrative and instructional coherence. For instance, before accessing the main laboratory to conduct DNA testing, the user first needed to prepare a plant specimen. Similarly, users were required to equip a lab coat to avoid contamination, and failing to do so would prevent progression to the next task. These mechanics not only supported the educational goals of the application but also reinforced logical dependencies between actions, enhancing realism and immersion.

As part of this design phase, a conceptual model [56] [16] was developed to visualize and clarify how users would interact with the prototypes as well as how the system would respond according to user's actions. This allowed to map out the core functionality, interaction flow, and system behavior from the user's perspective. This approach allowed the model to remain unified while still accounting for variations in user input and movement. The conceptual model was refined and iterated throughout the design process.

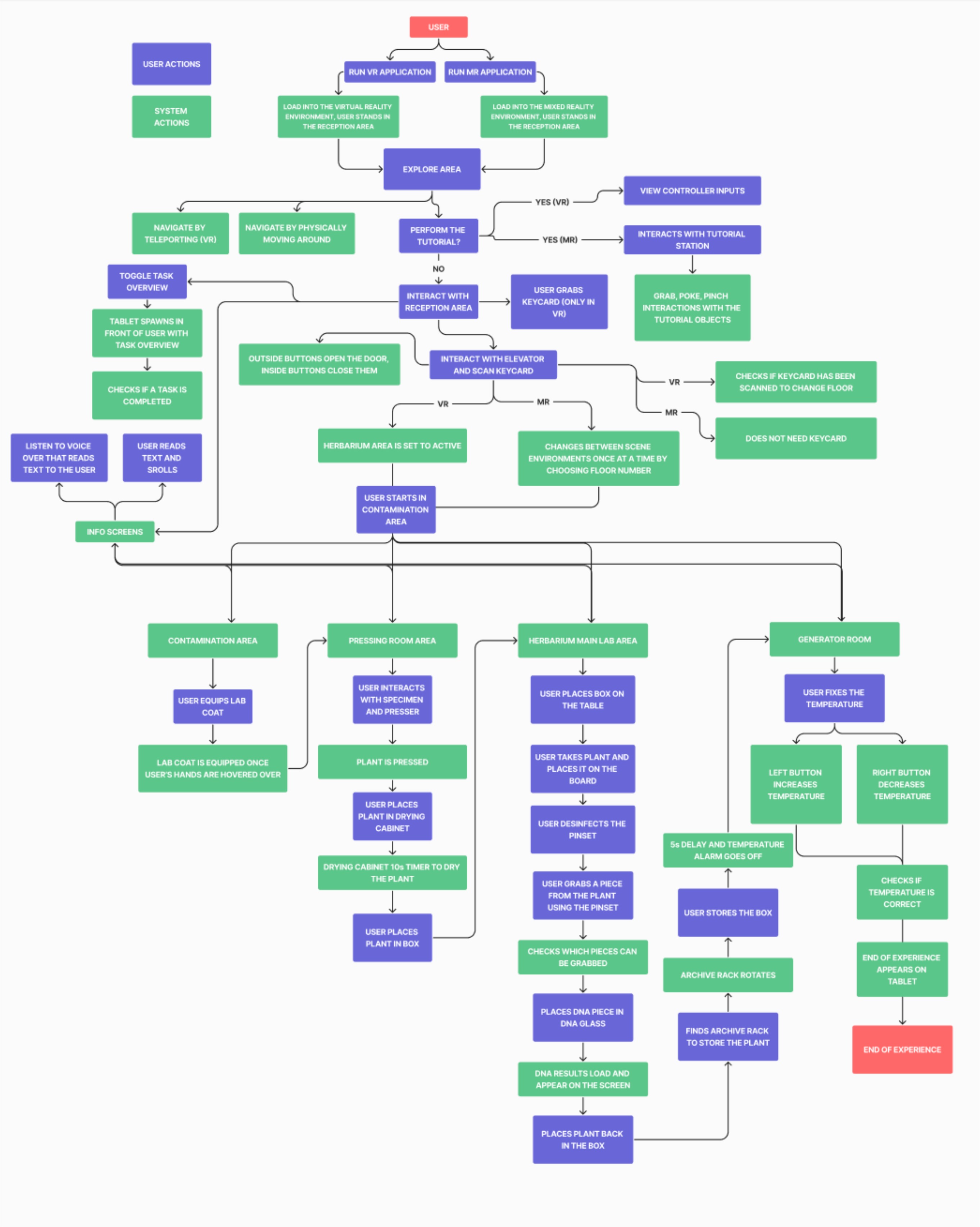

USER ACTIONS
SYSTEM ACTIONS
USER
RUN VR APPLICATION
RUN MR APPLICATION
LOAD INTO THE VIRTUAL REALITY ENVIRONMENT, USER STANDS IN THE RECEPTION AREA
LOAD INTO THE MIXED REALITY ENVIRONMENT, USER STANDS IN THE RECEPTION AREA
EXPLORE AREA
YES (VR)
VIEW CONTROLLER INPUTS
NAVIGATE BY TELEPORTING (VR)
NAVIGATE BY PHYSICALLY MOVING AROUND
PERFORM THE TUTORIAL?
YES (MR)
INTERACTS WITH TUTORIAL STATION
NO
GRAB, POKE, PINCH INTERACTIONS WITH THE TUTORIAL OBJECTS
TOGGLE TASK OVERVIEW
INTERACT WITH RECEPTION AREA
USER GRABS KEYCARD (ONLY IN VR)
TABLET SPAWNS IN FRONT OF USER WITH TASK OVERVIEW
OUTSIDE BUTTONS OPEN THE DOOR, INSIDE BUTTONS CLOSE THEM
INTERACT WITH ELEVATOR AND SCAN KEYCARD
VR
CHECKS IF KEYCARD HAS BEEN SCANNED TO CHANGE FLOOR
CHECKS IF A TASK IS COMPLETED
VR
MR
MR
DOES NOT NEED KEYCARD
LISTEN TO VOICE OVER THAT READS TEXT TO THE USER
USER READS TEXT AND SROLLS
HERBARIUM AREA IS SET TO ACTIVE
CHANGES BETWEEN SCENE ENVIRONMENTS ONCE AT A TIME BY CHOOSING FLOOR NUMBER
USER STARTS IN CONTAMINATION AREA
INFO SCREENS
CONTAMINATION AREA
PRESSING ROOM AREA
HERBARIUM MAIN LAB AREA
GENERATOR ROOM
USER EQUIPS LAB COAT
USER INTERACTS WITH SPECIMEN AND PRESSER
USER PLACES BOX ON THE TABLE
USER FIXES THE TEMPERATURE
LAB COAT IS EQUIPPED ONCE USER'S HANDS ARE HOVERED OVER
PLANT IS PRESSED
USER TAKES PLANT AND PLACES IT ON THE BOARD
LEFT BUTTON INCREASES TEMPERATURE
RIGHT BUTTON DECREASES TEMPERATURE
USER PLACES PLANT IN DRYING CABINET
USER DESINFECTS THE PINSET
5s DELAY AND TEMPERATURE ALARM GOES OFF
DRYING CABINET 10s TIMER TO DRY THE PLANT
USER GRABS A PIECE FROM THE PLANT USING THE PINSET
CHECKS IF TEMPERATURE IS CORRECT
USER STORES THE BOX
USER PLACES PLANT IN BOX
CHECKS WHICH PIECES CAN BE GRABBED
ARCHIVE RACK ROTATES
END OF EXPERIENCE APPEARS ON TABLET
PLACES DNA PIECE IN DNA GLASS
FINDS ARCHIVE RACK TO STORE THE PLANT
END OF EXPERIENCE
DNA RESULTS LOAD AND APPEAR ON THE SCREEN
PLACES PLANT BACK IN THE BOX

Figure 4.11: Conceptual model

4.7 Interactive functionality and technical integration

This section outlines the core interactive functionalities implemented in both the virtual (VR) and mixed reality (MR) prototypes. The interactions were developed using Unity[71] in combination with the Meta XR All-in-One SDK[37], and were used to add grab, ray, poke, socket and pinch to the immersive experiences. After installing the Meta XR SDK, the default Unity camera was replaced with the 'OVRCameraRigInteraction' prefab, which supports HMD tracking, hand tracking, and controller visualization. This prefab includes built-in interaction features, reducing the need for custom implementations. To enable interactions on specific GameObjects, components like the 'Interactable Unity Event Wrapper' were used to link grab or poke events to Unity events without extra scripting.

4.7.1 Hand tracking & controller-based interactions

Hand tracking and its associated interaction modalities played a central role in the development of the MR prototype and were partially emulated in the VR prototype using physical controllers. These interactions aimed to mirror real-world gestures and enhance the user's sense of embodiment, supporting a more natural and intuitive learning experience within the herbarium context.

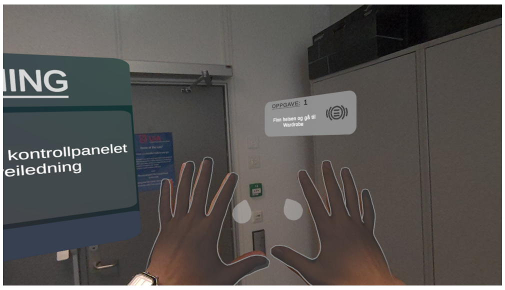


Figure 4.12: Visualization of hand tracking in use (MR prototype)

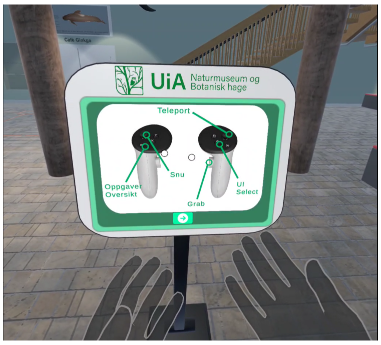


Figure 4.13: Virtual representation of hands manipulated by physical controllers (VR Prototype)

Grab interactions

Grab interactions allowed users to pick up and move virtual objects using either their hands (in MR) or physical controllers (in VR). Users can grab and reposition various items, such as the plant, plant presser, and the plant storage box. The interaction was consistent across both prototypes, offering direct manipulation of objects in space.

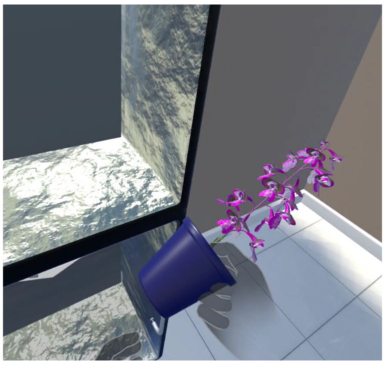


Figure 4.14: Grabbing the plant using controllers (VR Prototype)

Grab pose

The Meta XR All-in-One SDK [37] includes a custom hand pose tool that was used in the MR prototype to enhance realism and improve object affordance. This feature allows developers to assign predefined hand poses to specific grabbable objects, so when users grab an item, such as the lid to the storage box, their virtual hand automatically snaps into a recorded pose that aligns naturally with the shape of the object and intended grip. This not only improves visual realism but also helps communicate how an object is meant to be held. The poses were created using a built-in sample scene provided by Meta, which enables manual hand pose recording directly within the Unity editor.

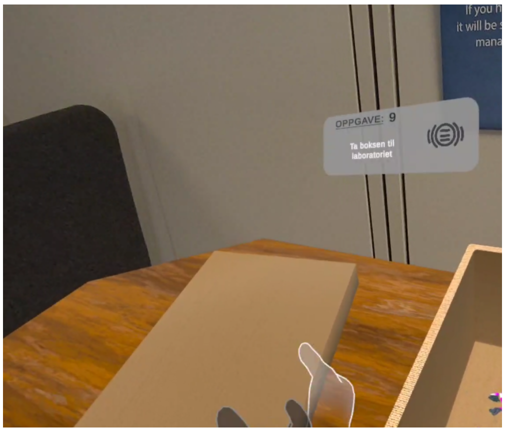


Figure 4.15: Predefined hand pose in a transparent white color (MR Prototype)

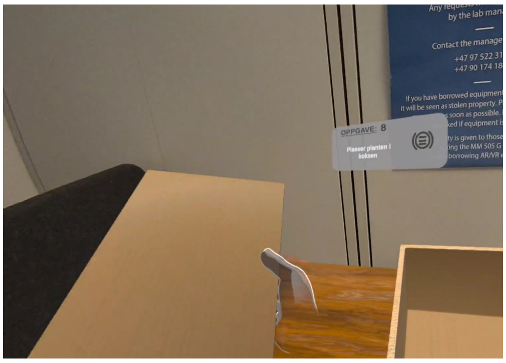


Figure 4.16: When the lid is grabbed it snaps to the pre-recorded grab pose (MR Prototype)

Poke interactions

Poke interactions were implemented to allow users to activate user interface (UI) and GameObject elements by pointing and pressing with their index finger (MR Prototype) or by triggering the trigger button using the controllers (VR Prototype) which created a poking gesture automatically. This interaction was further used for interacting with elevator buttons, temperature control panels, and hub screens, the latter of which also supported vertical scrolling—similar to touchscreen gestures on a smartphone. Poke interactions were available in both the VR and MR prototypes and adapted to work with controller input or hand tracking, depending on the platform.

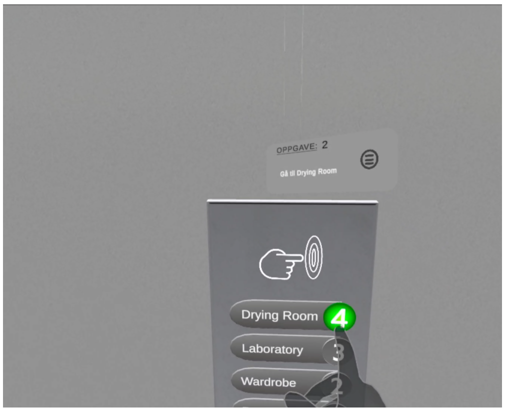


Figure 4.17: Poke interaction using hand tracking (MR Prototype)

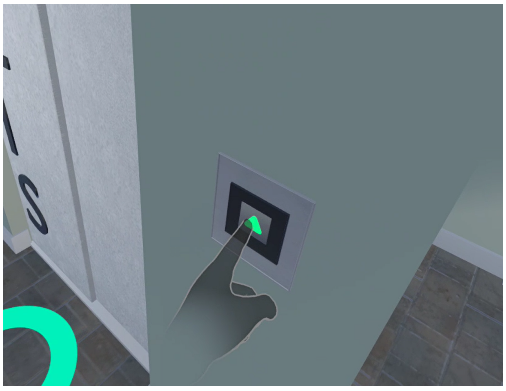
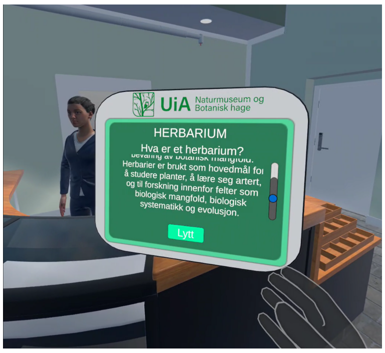


Figure 4.18: Poke interaction using the controllers (VR Prototype)

Ray interactions

Ray-based interactions were used exclusively in the VR prototype. These allowed users to interact with distant objects, particularly the info screens which were UI elements, or to navigate the environment using teleportation. This interaction was helpful for maintaining comfort and accessibility within the fully virtual environment, where spatial movement was otherwise limited.



HERBARIUM

Hva er et herbarium?

bevaring av botanisk mangfold. Herbarier er brukt som hovedmål fo å studere planter, å lære seg artert, og til forskning innenfor felter som biologisk mangfold, biologisk systematikk og evolusjon.

Figure 4.19: Ray interaction with the info screens (VR Prototype)

Pinch interactions

Pinch interactions were used only in the MR prototype, enabled through hand tracking. This gesture allowed users to manipulate specific elements with precision, most notably the lock mechanism on the plant presser. The pinch gesture simulated fine-motor tasks that mimics real world operations.

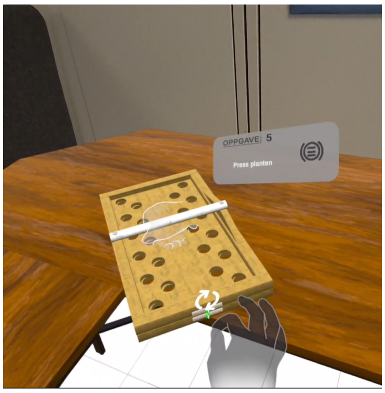


Figure 4.20: Pinch interaction being used to unlock the plant presser (MR Prototype)

Socket interactions

Socket interactions were used to guide the correct placement of items. Examples include placing the plant inside the press, placing the pressed plant into a box, and finally placing the plant onto a tray for DNA testing. These sockets ensured objects snapped into logical, predefined positions, making the process easier and understandable for the user to know exactly where the object needed to be placed. Socket interactions were available in both prototypes and adapted for controller-based input in VR and hand tracking in MR.

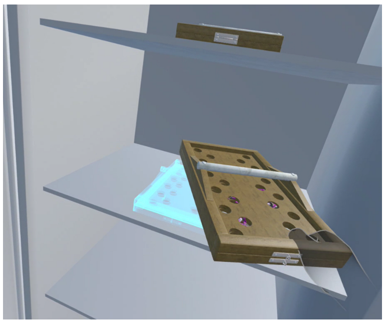


Figure 4.21: Socket interactable visualization (VR Prototype)

Multiple interaction manipulation

Certain interactive objects within the prototypes were designed to support multiple interaction types, allowing for more complex and realistic task simulations. These objects, such as the tweezers and the spray bottle used during the DNA analysis of dried plants, were specifically designed to respond to a combination of grab, pinch, and trigger-based interactions. For example, the tweezers must first be picked up using the grab interaction. Once held, users can pinch with the index finger and thumb to open and close the tweezers arms, enabling them to isolate and extract a portion of the plant sample for testing. The spray bottle, which was imported and adapted from the Meta XR All-in-One SDK [37], is grabbed with a standard grab interaction, and the index finger is used as a trigger to spray disinfectant. It was further customized to detect specific objects, such as the tweezers, and respond accordingly when sprayed on them, mimicking real-life sanitization procedures. These objects were developed to function seamlessly with both hand tracking in MR and controller-based interaction in VR, ensuring consistency between both prototypes.

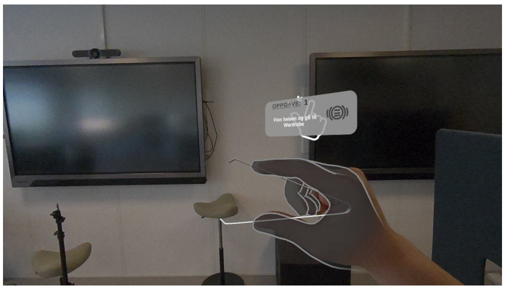


Figure 4.22: Tweezers being grabbed using grab interaction (MR Prototype)

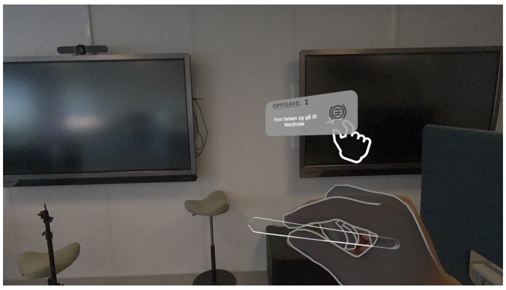


Figure 4.23: Tweezers being pinched while grabbed (MR Prototype)

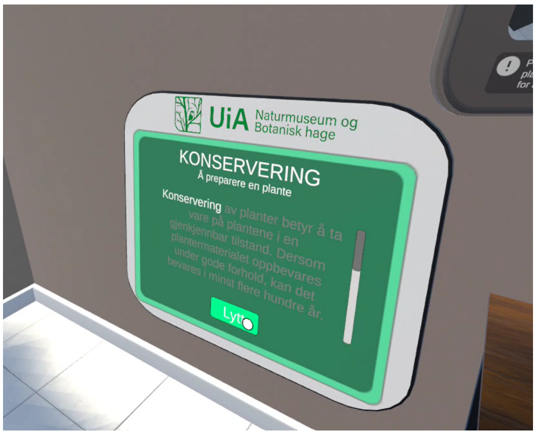
4.7.2 Navigation

Navigation, or locomotion refers to the way users move through and interact with space within the environment. Each of the two prototypes employed a different approach to locomotion. The VR prototype relied on the use of teleportation as a means of locomotion since the user is stationary within the physical world. The main reason for implementing teleportation in contrast to continues movement was to try and diminish the risk of cybersickness, which is a term used to describe discomfort such as nausea or headache when interacting withing a digital environment. In contrast, the MR prototype utilized room scaled movement, allowing users to physically walk around and interact with a virtual environment that is spatially mapped onto their real-world surroundings. This approach enabled more natural movement.

Taking advantage of the spatial mapping and pass-through capabilities provided by the Meta Quest 3[35], the researchers were able to scan a physical environment and anchor virtual objects directly within the real world. To access and utilize the scanned environment data stored on the Quest 3, the Meta XR All-in-One SDKcitemeta2025xr offers essential building blocks such as the MR Utility Kit, Room Model, and Pass-through system. These components, when integrated into Unity[71], enable functionality such as placing specific 3D models at predefined anchors, real-time tracking of the headset, and activation of pass-through vision. This allows users to physically walk around the environment as if they are part of the digital-physical hybrid space, supporting a more natural and embodied form of locomotion.

4.7.3 Audio & voice over text script

Voice-over narration was used across both prototypes, particularly in informational hub screens strategically placed throughout the environment. These narrations provided spoken explanations of key topics such as contamination prevention, herbarium procedures, DNA extraction, plant drying processes, and archiving protocols, offering users the option to either read the screen text or listen passively. This dual-modality approach accommodated different learning preferences and supported accessibility. AI-generated voiceover were created using a free text-to-speech platform called Narakeet [44]. To complement the audio, a custom text highlighting effect was implemented in Unity using TextMeshPro and scripting. This effect visually synchronized the spoken words with the on-screen text by gradually changing each character's color from a default shade to a highlight color in real-time as the audio played. The script calculated the duration of each character based on the total audio length and iteratively updated the vertex colors of visible characters, creating therefore a dynamic and readable 'karaoke-style' effect aligned with the voiceover timing.



Konservering av planter betyr å ta vare på plantene i en gjenkjennbar tilstand. Dersom plantermaterialet oppbevares under gode forhold, kan det bevares i minst flere hundre år.

Figure 4.24: Text-to-speech highlighting effect

In addition to voice-overs, contextual audio feedback was integrated throughout the experience to reinforce user actions and enhance immersion. Examples include button press sounds, task completion chimes, elevator door sounds, system startup cues for the drying cabinet, and alarm signals triggered by temperature malfunctions. These audio cues provided real-time feedback and helped orient users within the experience. All sound effects imported from free websites are listed in Appendix J.

4.7.4 User guidance

User guidance was an essential aspect of the prototype design in order to support intuitive interaction, reduce cognitive load, and foster task success. This guidance was implemented through a combination of voice-over narration, contextual audio feedback, interactive tutorials, and in-world visual interface elements.

Tutorial

The two prototypes featured distinct tutorial systems tailored to their interaction modes. The VR Prototype tutorial screen is presented at the beginning of the experience. This screen provides a visual guide to the controller button mappings for core interactions—namely grab, poke, and raycast (distance interaction)—to ensure users are familiar with the control scheme before entering the virtual environment.

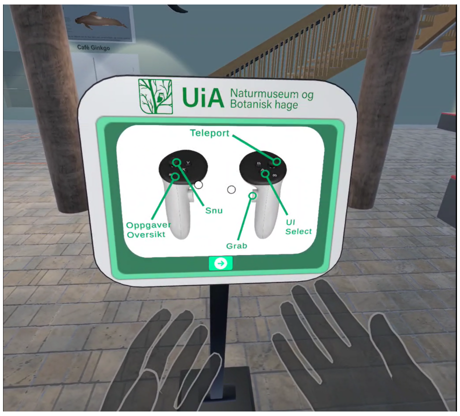
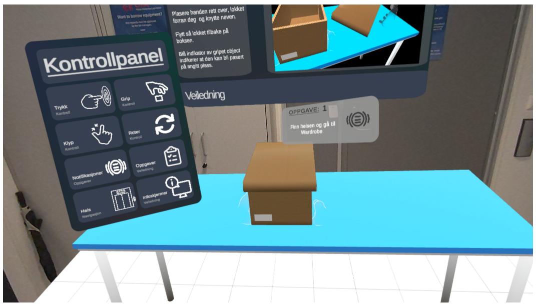

Café Ginkgo
UiA
Naturmuseum og Botanisk hage
Teleport
Snu
Oppgaver Oversikt
Grab
UI Select

Figure 4.25: Tutorial screen (VR Prototype)

The MR prototype has a dedicated tutorial station that is located on the first floor (the 'reception' area). Here, users encounter a control panel with buttons corresponding to each interaction type implemented in the prototype: poke, grab, pinch, rotate, and a special interaction labeled 'Oppgaver' (which demonstrates how to summon the menu by facing the left palm toward the user and pinching the left thumb and index finger when the menu icon appears). Additional buttons on the panel introduce the elevator system, informational hub screens, and the persistent notification UI displayed in the user's field of view.


Kontrollpanel
Trykk
Kontroll
Grip
Kontroll
Klyp
Kontroll
Roter
Kontroll
Notifikasjoner
Oppgaver
Oppgaver
Veiledning
Heis
Navigasjon
Infoskjermer
Veiledning
Veiledning
OPPGAVE: 1

Plasere handen rett over, lokket forran deg og knytte neven.

Flytt så lokket tilbake på boksen.

Blå indikator av gripet object indikerer at den kan bli pasert på angitt plass.

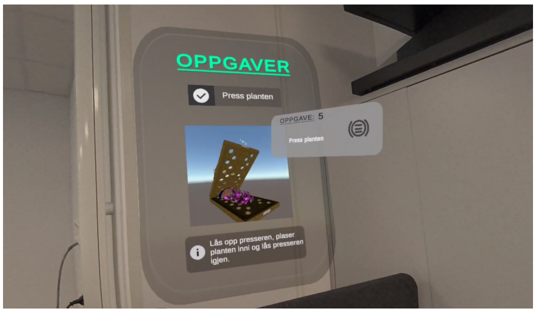
Finn heisen og gå til Wardrobe

Figure 4.26: Tutorial station (MR Prototype)

The difference in tutorial design across the two prototypes was primarily influenced by time constraints and the developmental complexity of the MR prototype. While the MR prototype was still in development, user testing was conducted on the VR prototype, and the feedback gathered during these sessions informed the ongoing MR development. This feedback revealed that many users struggled to understand how to interact with the virtual environment. As a result, the tutorial in the MR prototype was designed to be more comprehensive and in depth, offering hands on guidance and interaction demonstrations to better support task execution.

User interface (UI)

In the MR prototype, a constant UI is placed in the upper-right corner of the user's vision, displaying the current task and a menu icon. This icon serves as a visual reminder that users can open the task menu by facing the left palm toward themselves and pinching the left thumb and index finger when the icon appears. This task menu can also be opened in the VR prototype. The menu provides detailed task information through text and images, enhancing clarity and guidance throughout the experience.

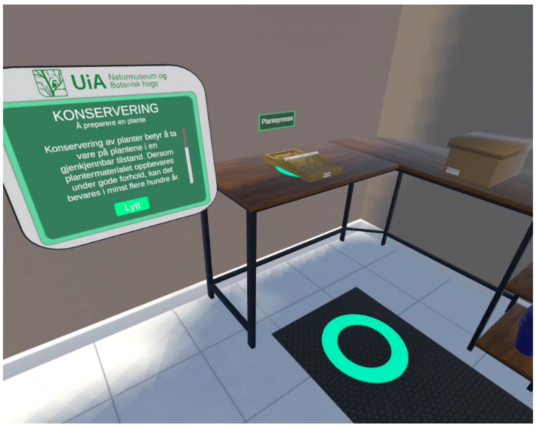


Lås opp presseren, plaser planten inni og lås presseren igjen.

Figure 4.27: Tablet overview (MR Prototype)

Moreover, other UIs to guide the user were integrated in the plant presser, which involves multiple interaction types. When interacting with the presser, it displays a pinch icon over its lock mechanism. When the user's hand is within interaction distance, the lock turns blue. Upon pinching, the pinch icon transforms into a rotation icon that animates in the required direction for unlocking. Once the lock is turned, the icon transitions to a padlock opening animation accompanied by a lock-opening sound. The same sequence occurs when locking the mechanism, with the rotation icon spinning in the opposite direction and the padlock opening animation is turned into a locking animation. In the VR prototype, the same process is applied but with grabbing instead of pinching. Another example is when the tweezers are grabbed, a pinch animation appears over them to indicate that the thumb and index finger can be used to manipulate the tweezers arms. This interaction allows users to grab a piece of the dried plant, simulating the process of preparing a DNA test sample.

In the VR prototype, the larger virtual space allowed for more expansive navigation. To guide users effectively through each scenario, animated green circles were used as visual cues, indicating where to go and which objects to interact with.



Konservering av planter betyr å ta vare på plantene i en gjenkjennbar tilstand. Dersom plantermaterialet oppbevares under gode forhold, kan det bevares i minst flere hundre år.

Figure 4.28: Circle with animation to guide users (VR Prototype)

4.8 C# scripting

C# (C-sharp)[38] is the primary scripting language used in Unity[71]. It is an object-oriented programming language developed by Microsoft, widely adopted for interactive application development due to its clarity, structure, and integration within the Unity engine. While Unity [71] and the Meta XR All-in-One SDK[37] provided a robust set of built-in components that significantly accelerated the development process, there remained a strong need for custom scripting to achieve the intended functional and experiential goals for both the VR and MR prototypes. These scripts were either developed from scratch or involved extending and modifying existing components from the Meta XR All-in-One SDK[37].

4.9 3D Modeling & assets

A significant portion of the assets and environmental components used in both the VR and MR prototypes were modeled from scratch using Blender [11], due to the limited availability of suitable pre-made models online. Visual references for these models were obtained through on-site visits to the natural museum in Kristiansand as well as through image research conducted online. This process was essential in ensuring a visually coherent and contextually accurate experience aligned with the educational objectives of the prototypes. To support a high degree of immersion and presence, particular emphasis was placed on realism and detail. As such, a considerable amount of development time was allocated to modeling, texturing, and optimizing both the environmental structure and interactive assets.

4.9.1 Environment modeling

By conducting field visits to the museum and capturing reference images of both the exterior and interior spaces of the herbarium, the researchers were able to conceptualize a layout that balances authenticity with design flexibility.

Given the nature of virtual reality, where the user is fully immersed in a digital environment, the VR prototype required both the external surroundings and internal laboratory spaces to be modeled in full. While the outdoor area remained largely faithful to the real-world museum setting, the internal spaces—including the laboratory, drying room, and DNA analysis stations—were re-imagined with modernized visual elements to enhance immersion and functionality.

In contrast, the MR prototype leverages room-scale scanning and overlays digital content onto the user's physical environment. As such, development efforts in this prototype focused more on crafting interactive assets that seamlessly integrate into scanned real-world spaces, enhancing realism and interactivity without duplicating the physical environment.

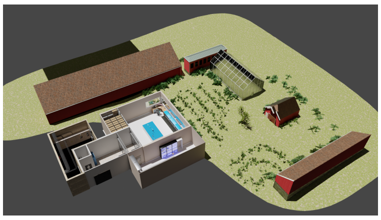


Figure 4.29: Birds eye view of the modeled lab environment in Blender

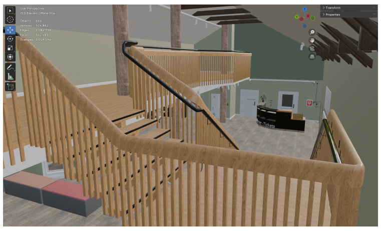


Figure 4.30: Museum entrance modeled in Blender, second floor

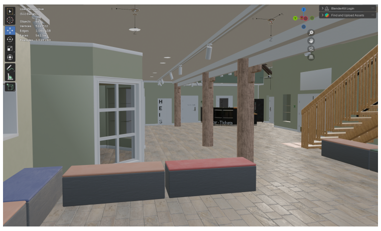


Figure 4.31: Museum entrance modeled in Blender, first floor

4.9.2 Assets modeling

The researchers placed equal emphasis on the design of in-world assets, which are critical for creating an engaging and interactive learning experience. Reference material for asset creation was obtained through direct observation, staff-guided tours, and documentation of the tools and procedures used at the herbarium, particularly in the domains of DNA testing, plant preservation, and archival processes.

All custom assets were created in Blender, with textures either generated manually or sourced from licensed texture libraries. Assets were UV mapped and textured in Blender to ensure optimal alignment and rendering when imported into Unity. Special care was taken with interactive objects—such as the plant presser, storage boxes, plants and laboratory tools—to ensure that their geometry was compatible with the interaction logic implemented in the prototypes. This included preparing grab points, and separation into individual parts for more complex multi-step interactions.

4.9.3 External assets

To reduce development time, some external 3D assets were sourced from public and commercial asset libraries, including Blender Kit [7], and Sketchfab [67]. Additionally, the receptionist 3D model character was imported from Mixamo [1]. However, these assets often required significant rework before being suitable for real-time performance on the Meta Quest 3. Most of these assets were utilized to fill the environments and make them more accurate and realistic, such as decorative plants around the reception area, fire extinguishers, fire alarms, books etc. A full list of imported external assets can be seen in Appendix J.

Some of the imported models were brought into Blender, where they were optimized by reducing polygon counts, removing hidden geometry, and replacing high-density mesh details (such as holes) with texture-based transparency. In some cases, partial reconstruction of assets was necessary to match the visual style and interactive requirements of the prototypes. This process ensured that all assets, whether custom or external, maintained both aesthetic consistency and runtime efficiency.

4.10 Challenges & solutions

Throughout the design and development process, several challenges emerged that required careful attention and creative problem-solving. As with any development project, obstacles are inevitable, however, the researchers adopted the philosophy from the beginning, that every challenge also presents an opportunity, whether to refine existing ideas or to generate entirely new ones. This mindset helped maneuver technical and design-related constraints but also contributed to more thoughtful and innovative solutions.

4.10.1 Scene change in the MR prototype

While the VR prototype allowed for a large, continuous environment in which users could freely navigate from one end to the other, this approach was not feasible in the MR prototype. Due to the constraints of physical space, users could only move within a limited, predefined area. Attempting to fit the entire VR environment into such a confined space would have compromised both realism and usability.

To address this challenge, the researchers introduced the concept of an elevator-based navigation system. When the user entered the elevator and selected a floor, the doors would close, providing a natural moment to transition between virtual scenes. This allowed the environment to change seamlessly while maintaining the illusion of a coherent spatial experience.

Technically, this was implemented by organizing each 'floor' as a separate parent GameObject in Unity, with all relevant assets grouped under it. Upon floor selection, the currently active floor was deactivated, and the newly selected floor was activated, all while the elevator doors remained closed. When the doors reopened, the user found themselves in a new environment, effectively simulating vertical movement and preserving immersion within the limited physical space available in the MR setting.

4.10.2 Optimization

To ensure smooth performance and usability on the Meta Quest 3, a standalone device with limited processing power, several optimization techniques were employed throughout the development of both prototypes. These strategies were essential not only for maintaining acceptable frame rates and reducing latency, but also for preserving a high level of presence and immersion. In immersive environments, even minor performance drops or rendering delays can disrupt the user's sense of 'being there' in the virtual or mixed environments. Therefore, efficient optimization played an important role in ensuring that interactions felt seamless and environments remained believable and engaging.

Baked Lighting

Baked lighting [74] was used to simulate realistic lighting and shadows without requiring real-time computation. Since the lighting conditions remained static, baking light-maps allowed the project to offload rendering complexity and significantly improve runtime performance.

Topology optimization

All custom and external 3D models underwent topological optimization in Blender prior to integration. Unnecessary geometry, such as unseen internal faces or overly dense mesh detail were removed. In some cases, geometry with holes or cutouts was replaced by using alpha-masked textures, therefore reducing polygon count while preserving visual fidelity.

Static batching

Objects that remained stationary and shared the same material/texture were marked as static in Unity and grouped for static batching [73]. This allowed Unity to combine them into fewer draw calls during rendering, reducing the overall load on the CPU. Elements such as structural walls, boxes, and decorative props, improving scene performance without affecting visual quality.

GPU instancing

For repeated objects using the same material and shader, GPU instancing [72] was enabled. This technique allowed the GPU to render multiple copies of the same mesh in a single draw call. Instancing not only reduced draw calls but also improved GPU performance by minimizing memory duplication.

Occlusion culling

To further optimize rendering performance, occlusion culling [75], as illustrated in figure 4.32, was implemented in the VR prototype. This technique prevents the system from rendering objects that are not currently visible to the user, such as those hidden behind walls or large structures, thus reducing unnecessary draw calls and GPU workload. By avoiding the rendering of hidden geometry, the system maintained higher and more stable frame rates, which is critical for preventing motion sickness and maintaining immersion, particularly on standalone headsets like the Meta Quest 3.

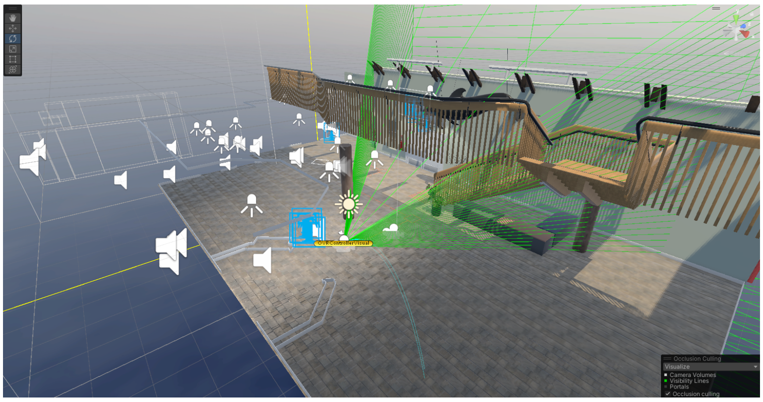


Figure 4.32: Occlusion culling example (VR Prototype)

Chapter 5

Findings & Discussion

This chapter presents the findings of the study to answer the research questions, drawing from data collected in preliminary user interviews at the museum and user testing sessions across both iterations of the prototypes, including pre and post-test interviews, observations and questionnaires (Appendices K - N). Additionally, research from the state-of-the-art including studies and theoretical frameworks were used to support the analysis and interpretation of the results.

5.1 RQ1 - How can mixed and virtual reality experiences be effectively designed and developed to facilitate active learning in educational and museum environments?

5.1.1 A virtual herbarium: summary of insights from preliminary user interviews to validate requirements

To inform the design of the immersive prototypes and ensure alignment with user expectation and needs, user interviews were conducted early in the project in parallel with the development phase. These interviews took place at the Natural History Museum in Kristiansand and involved six participants of the target group. Respondents were randomly selected at the museum and asked to answer some questions. The purpose of the interviews was to validate the initial design direction, explore user interest in the proposed herbarium scenario of use and user interaction modalities approach, and overall gather feedback on preferences, expectations, and the potential role of immersive technologies in educational museum contexts. A summary of the user interviews translated to english can be seen in Appendix N.

Topic 1: About the herbarium

1 - Have you visited a natural museum before? If so, how frequently?

All six participants indicated that they have visited a natural museum before. However, most of them do not visit frequently. Participant 1 and 2 expressed a particularly positive relationship with natural museums, one mentioning regular visits both for nature and relaxation, and the other mentioning international experience with natural museums. Other participants emphasized occasional or infrequent visits, often influenced by external factors such as good weather or general interest. **Interpretation:** While natural museums are generally viewed positively and are familiar to participants, they may not be a regular destination for many. This highlights a potential opportunity for the integration of immersive technologies like virtual and mixed reality to enhance accessibility, engagement, and repeat interest, especially for younger audiences. The varying frequency of visits also implies differing levels of familiarity with the museum's content and environment, which should be taken into consideration when designing learning experiences that aim to be inclusive and engaging for both regular and first-time users.

2 - Do you care about plants? Is it something that interests you when you visit the museum? Most participants expressed a clear interest in plants, with four out of six participants indicating some enthusiasm. Participant 1, for example, showed high engagement, mentioning a personal interest in wild plants and even using an identification app called 'Kvitromat' to learn about them. Participant 4 highlighted a personal connection by mentioning about a home garden. Participant 6 also expressed interest in both plants and flowers. One participant, namely participant 3, had little interest, while participant 5 stated they were not very interest in plants and preferred visiting the museum for animal exhibits. **Interpretation:** It suggests that the majority of participants have an existing appreciation or curiosity toward plant life, which is a promising indicator for the educational value of a virtual herbarium experience. This intrinsic interest can be leveraged to deepen engagement through interactive and exploratory content. However, the mixed responses also might highlight the need to consider multimodal appeal, meaning for example integrating storytelling and guided interactions to ensure the experience remains engaging even for users who may not initially be drawn to botanical content.

3 - Are you familiar with the herbarium at the natural museum? All six participants reported that they were not familiar with the herbarium at the museum. While two mentioned having learned about herbariums previously in school, none were really aware of the specific herbarium located at the museum. This may be due to it being located in a closed department. **Interpretation:** It suggests a lack of public awareness about the herbarium, even among museum visitors.

4 - The herbarium has a closed department due to sensitive and/or fragile specimens etc. Would it be something interesting to explore if you could? Out of six participants, four showed no interest in exploring the herbarium's closed department, often stating it was not for them or that they would prefer to read about it online. Two participants expressed clear interest, stating they would like to see what happens in this restricted space if it were accessible. **Interpretation:** Interest in accessing the closed department was limited, suggesting that such content may appear to a specific target of users. However, for those who are curious, access could provide meaningful insights and learning possibilities.

5 - Since this area is inaccessible, would a digital interactive alternative be appealing/interesting? Four participants responded positively to the idea of a digital interactive alternative. Two participants simply responded 'yes', while two others expressed that it would be a good and engaging solution. However, two participants showed no interest in such an alternative. **Interpretation:** There is a general openness toward using digital solutions to access otherwise restricted content. While not universally appealing, the idea of a virtual alternative was positively received by most, indicating a potential for engagement through interactive experiences, especially when physical access is limited.

Topic 2: About learning preferences

6 - How do you usually go about learning something new? (e.g. Reading text, looking at videos, digitally interacting etc). Most participants reported a preference for digital and visual learning formats, such as reading on Wikipedia, watching YouTube videos, or reading digitally. Several participants mentioned using multiple senses or modalities to enhance learning, combining reading, watching, and interacting physically. One participant highlighted the benefit of learning through interaction with others, while another emphasized the growing importance of visual and interactive methods like videos. **Interpretation:** The responses reflect a clear trend toward multimodal and visually rich learning strategies, reinforcing the relevance of using immersive technologies in educational settings. This preference for dynamic content aligns well with the use of virtual and mixed reality to support active and engaging learning experiences.

7 - Do you prefer to learn by getting specific instructions or do you prefer to explore at your own pace? Four out of six participants expressed a preference for learning at their own pace, though some mentioned this depends on the context or that they appreciate having some structure at the beginning. Two participants leaned more strongly toward specific instructions, especially in the early stages of learning or overall. One participant clearly preferred structured guidance throughout. **Interpretation:** The majority of participants favored flexible, self-paced learning, though some valued having initial guidance. This indicates the importance of designing immersive learning experiences that offer a balance between autonomy and structure.

8 - Do you find it easier to remember information when you interact with objects and environments rather than just reading or watching a video? Why or why not? Most participants agreed that interacting physically with objects and environments helps them remember information better. Participant 5 and 6 explicitly emphasized the value of physical engagement for memory retention. Participants 3 and 4 simply agreed without elaboration. Participant 2 preferred reading and watching. Participant 1 preferred apps and reading but also referenced learning through app interaction with nature-related content. **Interpretation:** The findings support the idea that embodied learning, a concept which emphasizes learning though physical interaction and sensory engagement with the environment, can enhance memory retention by grounding abstract knowledge in concrete, bodily experiences. This is consistent with the theory of embodied cognition, which suggests that cognitive processes are deeply connected to our motor systems and physical actions [84], and aligns with experiential learning theory, which highlights the role of active experimentation and direct involvement in reinforcing understanding and recall [26].

Topic 3: About the VR/MR technology

9 - What do you think of when you hear the terms “Virtual Reality” and “Mixed Reality”? The responses revealed mixed levels of familiarity with the terms. Participant 5 demonstrated a clear understanding of both VR and MR, while others showed only partial understanding or confusion. Participant 3 associated VR/MR with interacting in non-physical environments, and participant 6 described it vaguely as a ’fantasy world.’ Two participants were unfamiliar with the terms, and one openly expressed disinterest.**Interpretation:** The varied responses suggest a lack of widespread understanding or familiarity with immersive technology concepts among general museum visitors. Not all users are experienced or are familiar, so it is important to design experiences always having in mind that the user is a beginner.

10 - Have you used virtual reality before? Out of the six participants, four had never used VR before. One of them 4 reflected on potential future applications in elderly care, despite their lack of personal experience. Two participants had tried VR previously. Participant 5 described a positive and comfortable experience without motion sickness, while participant 6 called it an amazing experience with immersive and visually pleasing environments. **Interpretation:** These findings show that VR remains a novel experience for many museum visitors. However, those who have tried it described it positively. This indicates strong potential for first-time user engagement, but also underscores the importance of providing clear instructions to accommodate unfamiliar users.

11 - In a VR/MR experience, would you prefer interacting using controllers or your hands, and what would you expect from this interaction?
Most participants expressed a clear preference for hand-based interaction over controllers, citing reasons such as it feeling more natural or intuitive. Participant 3 mentioned that both options could be useful depending on the context. Another one, participant 4, highlighted that hands might be easier for older users, while participant 6 was unsure and did not provide a clear preference. **Interpretation:** There is a strong inclination toward natural hand-based interaction, which aligns with the goals of mixed reality experiences that emphasize embodiment and intuitive control. Designing for gesture-based input may enhance user comfort and accessibility, particularly for new or less tech-savvy users.

12 - Some VR applications allow users to physically move around a scanned version of their real-world space (spatial scanning), while others keep users stationary with controllers. Which method do you think would work better for an educational setting and would you prefer to move naturally within the space or explore while remaining seated? Why? Participant 1 and 2 showed no interest in the topic. Among the remaining four, three preferred moving around physically, but emphasized the importance of having the option to choose or ensuring the experience felt safe. Participant 6 preferred a stationary setup with controllers, finding it simpler and likely more comfortable. **Interpretation:** There is a moderate preference for room-scale movement, particularly when it supports learning through exploration. However, participants also valued choice and safety, suggesting that offering flexible interaction options (seated or standing) may increase accessibility and comfort.

13 - Do you think VR/MR would be a good solution for you when

learning something new? Four participants responded positively, with three expressing strong agreement that VR/MR would be effective for learning. Participant 4 also agreed and highlighted the benefit for younger users or those who struggle with traditional learning methods. Participants 1 and 2 did not feel it would suit their own learning style, but both acknowledged that VR/MR could be valuable and engaging for younger audiences, particularly children and teenagers. **Interpretation:** The responses indicate a generally favorable perception of VR/MR for learning, especially among younger users or individuals with alternative learning preferences. Even participants less inclined to use VR themselves recognized its educational potential.

14 - What do you think would make a good VR/MR program when learning something? Participants emphasized a combination of interactivity, realism, and usability as essential qualities of an effective VR/MR learning experience. Participants 1 and 2 highlighted the importance of being able to freely explore and interact within the environment. Participants 3 and 4 focused on engaging historical simulations. Participants 5 and 6 emphasized ease of use, hand tracking, and audio feedback as important design elements for improving comprehension and realism. Participant 6 also mentioned realistic models and lighting as enhancing factors. **Interpretation:** Participants value VR learning programs that are exploratory, intuitive, and multisensory. Features like audio feedback and visual fidelity contribute to immersion and ease of learning.

5.1.2 Selection of an immersive approach for effective learning: Key considerations based on user interviews

Based on the user interviews, this section reflects on key considerations when selecting an immersive approach for learning-focused experiences. While this study employed both VR and MR approaches, it may not always be feasible for developers to pursue both approaches when developing an immersive experience within an educational context of use. However for the purpose of this study, it was important to divide these user interaction modalities into two distinct approaches of the same scenario of use to come up with relevant findings and reflections. Could a VR approach be more feasible in contrast to MR, or the other way around? Based on the conducted user interviews, the researchers have interpreted that selecting the 'ideal' immersive approach is not always straightforward and depends on several key factors:

Firstly, understanding the context of use is fundamental. For example, whether the experience is intended for a public museum exhibit, classroom or other educational setting. Some participants were curious about exploring the herbarium digitally, while others were less interested, suggesting that the choice of approach should consider not only the physical setting but also how interesting and relevant the topic is for them. Furthermore, the scenario of use is also fundamental to keep in mind. What will the users be doing? Does it merely involve observing or do users actually participate in hands-on activities during the immersive experience? For the herbarium scenario of use, it is intended that users go through diverse hands-on scenarios. This could mean that MR could be a more appropriate and suitable choice due to its support for hand-based embodied interactions and spatial engagement. However if the physical space is limited, or users are expected to remain stationary, a VR approach can still simulate hands-on activities effectively through well-designed interaction metaphors. In this case, while the museum does not yet have a dedicated space for an MR experience exhibit, a VR approach is for the time being a more appropriate approach.

Furthermore, another important aspect to keep in mind is the familiarity of users. During the user interviews conducted, participants showed varying levels of familiarity with immersive technologies, indicating that controller-based VR may be more suitable for general audiences with limited experience. At the same time, many participants emphasized the importance of interactive and hands-on learning. Moreover, preferences for seated use and ease of interaction also highlight the need for an accessible design. Finally, as understood in chapter 2, most learners have bimodal learning preferences meaning that they tend to involve diverse modalities and/or approaches when learning something new. Some participants expressed diverse learning preferences where reading, watching, and interacting are combined. This reflects the importance of taking such aspects in mind when designing an immersive experience, whether intended for VR or MR.

These reflections served as the foundation for the design strategies and decisions presented in the following sections, where each prototype was purposefully designed and developed to support active learning within its respective immersive VR and MR environment.

5.1.3 Immersive design strategies for effective mixed and virtual reality user experiences

This section discusses design strategies and decisions considered in this research study to produce effective immersive VR and MR learning environments.

Design for active learning in immersive experiences

The virtual and mixed reality prototypes were designed to support active learning by engaging users in meaningful, task-based immersive environments that simulate real-world herbarium procedures. Across both prototype approaches, learners take the active role of an herbarium researcher by exploring and interacting with a sequence of scenarios that communicate core concepts and procedures related to the herbarium. This is done both in the stationary controller-based solution and by physically navigating around within a dedicated space and interacting through hand-based interactions in the MR solution. This design encourages users to construct knowledge through experience and engagement, reflecting key principles of Kolb's [26] experiential learning and Wilson's [84] embodied cognition. The environments are structured to promote purposeful exploration, where users are guided through various stages and areas of the experience, beginning at the museum reception and progressing further through to the herbarium laboratory. Along the different scenario areas, users encounter interactive information screens that present essential theoretical content through text and audio, helping scaffold their understanding and support task completion.

This is supported by design principles 3 - Scaffold by introducing cognitive steps one at a time and 5 - Use guided exploration [22] as it helps users through the learning content by presenting content step by step while guiding their exploration and experience. While direct reflection activities were not embedded in the prototypes for example an in-game final quiz, post-test interviews prompted users to recall and reflect on the content they encountered, which encourages critical thinking and reinforces the learning process. This served as a relevant alternative to allow users to reflect on their experiences. Moreover, in addition to interacting with the diverse information screens, users physically perform actions throughout the several scenarios, such as wearing decontamination clothes, preparing a specimen, conducting a DNA test, disinfecting tools, adjusting the herbarium temperature and archiving specimens. These meaningful activities promote a deeper understanding of the content rather than merely reading or observing it, which is an approach further reinforced by embodied cognition [84] and kinesthetic learning [60].

These theoretical foundations are further validated by studies explored in Chapter 2. In the study by Bodzin et al. [8], it was demonstrated that immersive VR games significantly encouraged learners to actively engage with the content resulting in positive learning attitudes. In Bodzin's [8] VR game, students were involved in task-based problem solving set within a realistic environmental science context. Rather than passively receiving information, students navigated a virtual watershed, collected data, and actively interacted with digital representations of scientific tools. This reflected the importance of designing the herbarium prototypes to be task-based and exploratory, mirroring real herbarium procedures, improving both realism and relevance. Similarly, Makransky's [31] study found that VR simulations involving interactions significantly boost interest, self-efficacy, and memory retention when compared to traditional instructional methods.

These insights reflected the integration of design principle 3 - Scaffold by introducing cognitive steps one at a time [22] to scaffold learning gradually and support learner autonomy through guided exploration. In the herbarium experience, users were firstly introduced with a tutorial, where they were guided through the core interaction modalities. This initial exposure enabled users to become familiar with the interaction types before actually participating in the different herbarium scenarios. This also reinforces the decision for design principle 1 [22] which is to assume every learner is a beginner. Furthermore, user's weren't directly presented with the main scenarios. In contrary, early tasks were kept simple such as collecting and grabbing a keycard, going to the elevator and using simple interactions such as poking. As users further explored and entered the herbarium laboratory where the main scenarios took place, interactions became more cognitively demanding such as preparing the plant where a plant presser is utilized.

When considering active learning in the MR prototype, studies by Almufarreh [2] and Moro et al. [43] provided strong evidence that hand-based interaction with holographic content improved comprehension of complex topics and enhances learner engagement. These findings directly informed the design of the MR prototype, where users physically move within a scanned space and interact with virtual objects using natural hand gestures. For example, users grab tweezers with their virtual hands, pinch to manipulate specimen samples, or physically operate a spray bottle to disinfect equipment. These embodied interactions reflect real-world lab procedures and provide a deeper sensory and motor-based understanding of herbarium workflows. Such design decisions align with design Principles 11–13 [22], which emphasize kinesthetic involvement, body-based metaphors, and action-concept congruency as key strategies for facilitating conceptual learning. By mapping real gestures to meaningful tasks, the MR prototype supports active learning by engaging users in authentic, hands-on problem solving within a spatially grounded environment.

Furthermore, task design in the herbarium prototypes was informed by design principle 7 - Build for low stakes errors early on [22]. This approach aims to support learner confidence and encourage exploration without the fear of failure, which is essential for fostering active learning and iterative knowledge construction. In the herbarium experience, for instance, users are asked to select a valid plant fragment for DNA testing. If they choose incorrectly, the system responds with non-punitive feedback where a red circle appears around the object, signaling that the choice is invalid. However, progression is not blocked as users can immediately try again. A correct selection is confirmed with a green visual cue and a sound chime, reinforcing learning without causing frustration. This design reflects the trial-and-error learning loop emphasized by Schlachthoff et al. [61] in their museum-based RHINO-VR study, where visitors freely explored a virtual museum with minimal penalties, promoting curiosity-driven engagement and better conceptual understanding. By incorporating low-risk failure points into the herbarium scenarios, the prototypes encourage learners to reflect on their actions, make adjustments, and reinforce knowledge through repeated practice.

Role of interaction modalities for active learning in immersive experiences

As mentioned in chapter 2, there were some studies that explored the role of different interaction modalities in simple task-based activities. These studies helped shape design strategies for the integration of the different interaction modalities for each prototype. These interaction modalities played a fundamental role in allowing users to actively engage with the immersive environments. Both the VR and MR prototype designed in this study integrated distinct interaction modalities, namely controller-based input with teleportation in VR, and hand tracking with room-scale spatial scanning in MR, supporting embodied [19] and exploratory engagement. Voigt-Antons's et al.[79] study found that hand tracking can enhance immersion and intuitiveness by enabling more natural interactions, though it may be less precise than controller-based input. With the newer capabilities of the used Quest 3 compared to previous hardware, these insights were directly reflected in the MR prototype, where hand tracking was implemented to promote physical manipulation of tools, such as grabbing tweezers, pinching to extract plant DNA samples, and squeezing the disinfectant bottle. The same concept was adapted in the VR prototype, however instead of performing with hand gestures, users can grab certain tools using the controllers and when they are grabbed, the user has the ability to for example manipulate the tweezers by squeezing the trigger button. The more the trigger button is pressed, the more the tweezers' arms squeeze, giving it a dynamic feel and sense of agency as well as precision. This is further reinforced by design principle 15 [22], ownership and agency.

Exploration is important in an immersive learning experience as it gives users the freedom to explore the environment. Reinforced by design principle 5 [22], this was incorporated in both prototypes, where in VR, the user can explore the environment through teleportation while remaining stationary or by physically moving around a dedicated space in the MR prototype. Although teleportation is less physically embodied than room-scale walking, teleportation still supports active learning by encouraging spatial decision-making and goal-oriented movement. This design choice aligns with findings from Rey et al. [54] as it highlighted that spatial navigation, even when abstracted through non-physical locomotion, can improve memory performance and user engagement by allowing users to control the flow of their experience. In contrary, room-scale movement can also increase cognitive load which informed the structure of the MR prototype by balancing spatial freedom with clear task guidance and feedback, minimizing for a potential overload.

Both interaction modalities, whether gestural or controller-based, enabled users to actively engage with the herbarium content by exploring, manipulating, and reflecting. This emphasizes that active learning may not be specifically tied to a specific user interaction modality, but rather to how effectively the interaction design aligns with the users' needs, task demands, and cognitive processes. This perspective is highlighted on Varela Aldas's et al. study [77], who observed that both hand tracking and controller-based input can support learning depending on the context and the type of task, with neither being universally superior. Furthermore, Rey et al. [54] demonstrated that spatial navigation, such as room-scale movement, can enhance engagement, though it may also increase cognitive load. In the VR prototype, teleportation was employed to enable free exploration without physical strain, while the MR prototype allowed spatial navigation through real-world movement. Both approaches offered meaningful opportunities for active participation, which reflects the idea that it is the thoughtful integration of interaction and navigation and not the modality itself that best facilitates active learning in immersive environments.

Design elements & multimedia principles for active learning in immersive experiences

Interaction

Interactions are a fundamental design element in making active learning effective in the immersive experience prototypes. As described in chapter 4, a variety of interaction types shaped the way users interacted with the environment. Foundational interaction design decisions included the ability to grab objects, poke buttons and pinch to operate certain objects such as the plant presser. These interactions are important, because they promote physical engagement and task-based learning, which are key aspects of embodied cognition [84]. This type of interactive engagement is mirrored in the study by Varela-Aldas et al. [77], where participants completed daily tasks involving grabbing objects in a virtual kitchen. These interactions were improved along both iterations, allowing to create more accurate and realistic representations of interactions when manipulating the diverse objects within the herbarium. In correlation with these interactions, auditory feedback was integrated, recommended by design principle 9 [22], to further reinforce user actions and enhance realism. For example, sound cues were triggered when users pushed buttons or locked or unlocked the presser. Moreover, when users entered the elevator to progress to the herbarium, a sound was played to replicate a real-world use of an elevator and also when the plant was being dried, a generator sound was played to make it sound that the plant is being dried. This design decision was further supported by Makransky et al. [31], who noted that multi-sensory feedback in immersive environment can boost users' engagement and perceived realism, thereby allowing for a more memorable and meaningful learning experience.

Other interactions also played important roles, such as the socket interactions. For instance, inserting the plant specimen into the presser or placing the presser into the drying cabinet provided users with spatial cues and visual feedback of a ghost version of the object, aligning with Design Principle 9 - Give players unobtrusive, immediate, and actionable feedback, which emphasizes the value of unobtrusive and actionable system feedback. The same relied on the MR prototype where dedicated grab poses were illustrated in each grabbable object, insinuating to the user where to properly grab them.

Such practical and embodied interactions not only make the experience more interactive but also enhance memorability and realism while giving a sense of control to the user. In chapter 2, it was underscored that learners have different modalities in their learning preferences [49]. Therefore, combining kinesthetic with visual and auditory design elements can create a more engaging and inclusive learning environment. This multimodal approach aligns with the VARK model and supports active learning by catering to a broader range of learner needs, reinforcing understanding through multiple sensory channels.

Navigation

In addition to interactions, navigation was an essential design element across both prototypes, tailored to the spatial and experiential demands of each immersive environment. In the VR prototype, teleportation was implemented to allow users to explore a larger virtual environment comfortably. This method was intended to diminish the risk of cybersickness, a concern often associated with artificial movement in VR, as noted by Rey et al. [54], who found that teleportation reduces cognitive load.

In contrast, the MR prototype utilized spatial scanning and physical locomotion, allowing users to walk naturally within a smaller, room-scale environment. This design decision was informed by studies such as Moro et al. [43] and Almufarreh [2], which reflected the benefits of embodied spatial navigation for enhancing engagement and spatial understanding. Aligning with design principle 11 - Use the hand controls to encourage the learners to be "active", the inclusion of body-based navigation supports kinesthetic learning by encouraging active, physical participation.

Audio & text

Audio and text were also thoughtfully integrated in both prototypes to support diverse learning preferences while trying to minimize cognitive overload. As discussed in chapter 4, key information was presented through voice-over narration accompanied by option text on info screens. This design decision aligns with Mayer's multimedia learning principles [33], which emphasizes the importance of using complementary audio-visual channels to enhance retention without overwhelming the user. To further support this, Moreno and Mayer [34] found that combining audio with visual elements leads to better understanding compared to on-screen text alone. In both prototypes, users could listen instead of reading while doing activities, allowing them to focus more on the visual and interactive elements. This approach was also recommended by design principle 6 [22], which encourages minimizing excessive reading and using multimodal feedback to improve comprehension and engagement.

Visualization

Just as audio and text were thoughtfully integrated to guide attention and reduce cognitive load, visual design also played a crucial role in facilitating active learning across both immersive prototypes. Rather than attempting for photorealism, the environments were modeled to closely resemble the herbarium and museum settings, providing contextual grounding that enhances presence and supports user orientation. This balance between realism and clarity enabled users to recognize key objects and scenarios without being overwhelmed by excessive visual detail. While the prototypes may not replicate a physical visit to the herbarium, they tried to offer a structured and immersive environment where visualization becomes an active part of the learning process.

As emphasized by Gonçalves et al. [14], while higher visual realism can improve spatial understanding and immersion, it may also increase cognitive load and hinder learning if not aligned with the learner's capacity. This insight informed the decision to maintain moderate visual fidelity across both prototypes, realistic enough to reinforce the learning context, yet simplified to ensure focus on the educational content. Similarly, Makransky et al. [31] found that overly immersive visuals could reduce retention, further reinforcing the importance of careful visual calibration.

Visual cues were also used intentionally to support task progression. In iteration 2 of the VR prototype, green animated circles were introduced to guide users toward interactive hotspots and navigation points. These visuals complemented existing audio and textual guidance, with the goal of contributing to a cohesive, multimodal learning experience. Additionally, user interface overlays were applied contextually to label important objects, such as disinfectant sprays names or the specific plant that the users were going to prepare, helping users distinguish between items and remember their purpose. These decisions were recommended by design Principles 2, 5, and 13 [22], emphasizing clarity, guided exploration, and congruent mappings between visual design and task relevance.

5.2 RQ2 - To what extent does hand tracking and spatial scanning influence the users' perceived level of presence and engagement in the mixed reality experience compared to virtual reality interaction methods?

5.2.1 Summary of findings from user tests: Iteration one and two

Pre-test interview

Summary of findings: VR and MR Iterations 1 and 2
Participants across both VR and MR prototypes had varied backgrounds in terms of museum visits, use of digital tools, and experience with immersive technologies. While most had visited museums before, not all were familiar with natural history museums. Experience with digital and interactive tools

ranged from high confidence among gamers and developers to more limited exposure among others. Similarly, VR and MR familiarity spanned from advanced use and development to first time exposure.

In terms of learning preferences, many participants favored starting with simple explanations and diving deeper if the topic was interesting. Others preferred structured or hands on learning from the beginning. Most participants expressed a strong interest in modern interactive museum experiences, stating that they offered more engagement and learning potential than traditional formats like reading labels or watching videos.

Finally, when asked what makes a museum learning experience more engaging, participants consistently highlighted interactivity, visual design, physical exploration, and access to unique or hidden content. These elements were seen as crucial for boosting attention, enjoyment, and retention.

Observations from user tasks

Task 1: Explore the reception area and find the way to the herbarium lab

Iteration 1 VR:
All three participants (P1, P2, P3) encountered varying levels of difficulty in navigation. P1 experienced confusion due to a lack of spatial cues and struggled to locate the elevator. P2 followed the floor lines effectively but showed a clear preference for interaction over reading, skipping information screens. P3 attempted to explore freely but experienced some cybersickness and confusion with navigation and the teleportation system. While curiosity and willingness to explore were evident, issues with clarity, spatial feedback, and onboarding guidance limited the effectiveness of this task.

Iteration 2 VR:
Participants showed varying experiences navigating the initial reception area. P7 and P8 required significant guidance despite completing the tutorial. P7 explored freely but missed task cues, while P8 experienced confusion with teleportation and item interaction. P9 completed the task quickly but faced a critical boundary error, requiring a restart. P10 successfully navigated without issue. P11 expressed discomfort with controller-based rotation and lost the keycard, leading to brief confusion. Overall, challenges included interpreting the task flow, controller familiarity, and environmental feedback.

Iteration 1 MR:

All participants were able to navigate to the wardrobe via the elevator without difficulty. All three adapted quickly to the MR environment and used hand tracking effectively. P6 engaged with the reception info screen, while P5 skipped it entirely, demonstrating varying preferences for guidance material.

Iteration 2 MR:

All participants completed the task successfully. P12 initially spent time in the tutorial section and required a reminder to check the top-right notification and the task menu. P16 also needed initial guidance to interact with the tutorial buttons and overlooked the info screens until prompted. In contrast, P13 and P14 completed the tutorial independently and proceeded without difficulty. P15 engaged with the info screens and seemed satisfied. Participants P14 and P15 both expressed positive reactions through comments like 'damn' and 'nice,' indicating excitement and enjoyment.

Task 2: Equip the required outfit before entering the herbarium lab

Iteration 1 VR:

This task was generally executed successfully by all participants. P1 completed the task rapidly but skipped the contamination info screen, missing important contextual information. P2 attempted to interact with a non-interactive UI box, suggesting that some visual elements were misinterpreted as interactive. P3 completed the task smoothly and intuitively. While the task was beginner friendly, the feedback design could be improved to reinforce learning objectives like contamination prevention.

Iteration 2 VR:

This task was completed successfully by most participants, though the paths varied. P7 and P9 completed the task without issues, indicating smooth interaction. P8 experienced technical issues and required a restart. P10 and P11 struggled initially with orientation and room identification but succeeded through exploration and reading info screens.

Iteration 1 MR:

P4 and P6 completed the task without issue. P5 experienced some difficulty interacting with the info screen until they were reminded to use the poke gesture. This suggests that while most found the task intuitive, there was an initial learning curve for gesture control.

Iteration 2 MR:

Most participants found and equipped the outfit with ease, including P12, P13, P15, and P16. P14 briefly struggled with accessing the task menu and required guidance but completed the task afterward. P16 humorously mistook a real-world poster as part of the MR environment, which enhanced their engagement.

Task 3: Explore the pressing room and learn about the process of preparing a plant for research

Iteration 1 VR:

All three participants (P1, P2, P3) struggled with interaction mechanics and spatial understanding. P1 skipped the info screen and had issues operating the pressing machine, which lacked clear feedback after pressing the plant. P2 encountered a critical plant bug and required assistance with tool use. P3 experienced technical issues, including dropping items and being unable to recover them, leading to task failure. The pressing room task revealed significant breaks in presence due to bugs, lack of structured guidance, and unintuitive interaction design.

Iteration 2 VR:

This task surfaced more challenges. P7 had to rely heavily on external guidance, misunderstood task sequencing, and experienced a bug with the lab door. P8 misused objects, dropped the box multiple times, and had confusion over teleporting with items. P9 attempted to put the entire presser into the box, faced a critical bug, and needed a restart. P10 showed strong curiosity and enjoyed the environment but forgot drying steps. P11 experienced motion discomfort and had trouble with interaction.

Iteration 1 MR:

All three participants encountered varying levels of difficulty when interacting with the pressing machine, particularly its lock mechanism. P4 initially struggled with understanding how to open the press and became frustrated. They commented that the interaction was not intuitive and that users unfamiliar with the technology would likely face similar difficulties. P5 completed the interaction without major issues but did not fully understand that the dried plant needed to be removed from the presser before archiving, indicating confusion around the process sequence. P6 explored the environment actively and used both hands naturally, but needed guidance to open the press and encountered two critical errors, requiring a restart of the prototype.

Iteration 2 MR:

Both P12 and P13 experienced a critical bug with the presser that required restarting the application. P12 struggled with understanding what to do with the presser and needed a reminder to use the task notification and menu for guidance. P15 encountered a minor bug with the presser that requiring a workaround using a different presser. P16 faced issues with hand tracking due to the Meta Quest 3[35] hardware. P14 explored the environment extensively, demonstrating high engagement and curiosity. Despite the issues, all participants completed the task.

Task 4: Explore the main laboratory and learn about the process of taking a DNA test and archiving a prepared plant

Iteration 1 VR:
Participants encountered both navigational and interaction difficulties during this task. P1 and P2 forgot to bring the plant box and experienced issues with sliding doors, which either malfunctioned or required non-standard interaction like 'cheating' through the environment. P1 also skipped the disinfection step and had trouble with tool interaction. P2 required repeated guidance. P3 understood the overall task but skipped important info about plant storage and had trouble placing the DNA sample. Overall, poor task flow clarity, bugs, and missing spatial cues disrupted the learning process.

Iteration 2 VR:
Performance was smoother here. P7 made a mistake in disinfection but completed the task with light guidance. P8 used the environment and visual cues well but ignored the info screen for archiving. P9 completed the DNA test easily with the help of the menu. P10 demonstrated confident interaction and smooth progression. P11 enjoyed the process and visuals but mentioned slight motion discomfort.

Iteration 1 MR:
All participants encountered some level of difficulty during this task. P4 experienced a critical bug when the tweezers disappeared, preventing DNA testing. P5 preferred reading over listening and encountered minor usability issues with the box, but was able to continue. P6 had trouble identifying where to put the DNA piece and misapplied pinch interactions.

Iteration 2 MR:
All participants successfully completed the task, though some encountered minor challenges. P12 disinfected the plant instead of the tweezers. P13 needed help locating the DNA glass. P15 needed guidance to archive the plant cor-

rectly. P16 required a few attempts to place the DNA test piece on the glass. Participants expressed overall enjoyment and curiosity, as indicated by spontaneous comments like 'WOW' (P14) and 'this is cool' (P16).

Task 5: Find and explore the temperature room and fix the sudden decrease of temperature of the herbarium lab to finish the experience

Iteration 1 VR:
P1 had problems opening the door due to collider issues and encountered problems with temperature buttons that did not respond to being poked. P2 was momentarily distracted and experienced a teleportation bug but eventually figured out the temperature settings. P3 had minor trouble accessing the room but quickly identified the correct temperature using the info screen. Despite technical disruptions, most participants successfully completed the task, with room for improvement in physical control and environmental responsiveness.

Iteration 2 VR:
Most participants completed this task efficiently, though their approaches varied. P7 didn't know where the room was and disliked the voice-over option on the info screens. P8 relied heavily on visual cues and completed the task with ease. P9 found the room quickly and set the correct temperature by trial. P10 used the info screen and then explored other objects. P11 had to stand up for interaction due to poor alignment.

Iteration 1 MR:
All participants successfully completed the task. P4 and P5 navigated and adjusted the temperature without issue. P6 initially missed the correct temperature due to skimming the info screen but returned later for clarification.

Iteration 2 MR:
All participants managed to complete the task. P12 began by adjusting the temperature randomly before consulting the info screen, while P14 needed help locating both the temperature room and the correct temperature information. P13, P15, and P16 completed the task efficiently, demonstrating an increasing familiarity with gesture-based controls and spatial layout.

Questionnaire findings: Iteration one & two

All questionnaire findings from both iterations within both prototypes can be seen in Appendices K - N .

System Usability Scale (SUS) findings: Summarized scores

Prototype	Participant	SUS Score
VR Iteration 1	Participant 1	30
	Participant 2	95
	Participant 3	37.5
	Average	**54.1**
VR Iteration 2	Participant 7	45
	Participant 8	57.5
	Participant 9	70
	Participant 10	87.5
	Participant 11	57.5
	Average	**63.5**
MR Iteration 1	Participant 4	50
	Participant 5	77.5
	Participant 6	75
	Average	**67.5**
MR Iteration 2	Participant 12	82.5
	Participant 13	82.5
	Participant 14	87.5
	Participant 15	55
	Participant 16	82.5
	Average	**78**

Table 5.1: System Usability Scale (SUS) [29] Scores for VR and MR prototypes across iterations

Post-test interview

Q1: How was your experience using the prototype?

Iteration 1 VR:

P1 found the layout visually appealing but reported discomfort and confusion due to shaky visuals and unclear interactions, contributing to feelings of cybersickness. P2 enjoyed the experience overall but expressed difficulty focusing due to ADHD and preferred simpler, more structured instructions. P3 appreciated the visual and audio design and found the interaction creative, though their overall impression was moderate.

Iteration 2 VR:

P7 and P8 found the experience enjoyable but noted confusion due to unclear task instructions and an initial struggle with the controllers. P9 experienced a critical error during the experience which broke immersion, and also mentioned an overload of simultaneous audio feedback. P10 had a very positive experience and appreciated learning passively through interaction. P11 described the experience as fun but noted motion sickness and discomfort due to the rotation speed.

Iteration 1 MR:

All participants found the experience enjoyable, fun, and engaging. P4 appreciated the natural interaction but found the plant presser frustrating. P5 and P6 highlighted that the experience was fun and interactive, and P6 also felt that it was educational despite some interaction issues.

Iteration 2 MR:

All participants reported a positive and enjoyable experience. P12 and P14 mentioned being pleasantly surprised by the prototype's design and educational potential. P13 and P16 emphasized the hands-on experience and engagement. P15 pointed out minor technical limitations such as one-handed interactions and lack of plant-specific information. Criticisms included the synthetic voice on info screens (P14), minor bugs (P12), and text-heavy presentation (P12, P15).

Q2: How did you feel about using hand tracking/controllers in the experience? Did they feel intuitive or limiting in any way?

Iteration 1 VR:

P1 reported that controller usage became intuitive over time through trial and error. P2 found them intuitive and easy to learn but still recommended a tutorial for first-time users. P3 struggled with the controller logic and disliked the joystick design, needing assistance to understand how to use them properly.

Iteration 2 VR:

Participants had varied experiences with the VR controllers. P7 mentioned initial difficulties but adapted after a while and found the interaction better than traditional methods. P8 found the controls somewhat clunky but appreciated the button UI that helped reduce confusion. P9 liked that the interaction forced learning by doing, although they struggled with specific controller interactions. P10 felt the controllers were intuitive and aided retention. P11 thought the controllers were "ok" but not particularly intuitive and would prefer hand tracking if possible.

Iteration 1 MR:

P4 found it inconsistent and not very helpful for learning. P5 experienced an initial learning curve but found it intuitive after explanation. P6 preferred hand tracking over controllers and found it mostly intuitive.

Iteration 2 MR:
All participants found hand tracking intuitive and effective. P12 highlighted the surprising responsiveness, especially with the tweezers. P13 and P14 noted a preference for hand tracking over controllers. P15 mentioned it was easier to remember tasks when using hands. P16 described it as new but easy to adapt to.

Q3: How did it feel to physically move around to navigate around the environment?

Iteration 1 VR:
P1 preferred teleportation over continuous movement but still wished for more natural movement. P2 was comfortable being stationary but also expressed a desire to walk around. P3 disliked the stationary setup, felt overwhelmed, and experienced mild motion sickness.

Iteration 2 VR:
Participants had varied reactions to the stationary nature of the VR experience, with several expressing a desire for more freedom of movement. P7 expected to walk physically and found teleportation slightly strange at first; they also had to adjust their posture to reach elements due to a mismatch between virtual and real-world height. P8 initially felt restricted but adapted once they understood the teleportation mechanic. P9 appreciated teleportation over continuous movement, citing comfort. P10 expressed discomfort with being stationary, wished for more physical movement, and even mentioned feeling like they needed a seatbelt to prevent actual movement. P11 found it difficult due to incorrect height calibration, which required them to stand, impacting comfort. These reactions show that while some participants adapted to the constraints of VR, limited physical mobility remained a challenge for creating a fully immersive experience.

Iteration 1 MR:
Participants described the physical movement as intuitive and comfortable. None experienced cybersickness. P5 felt ’really there,’ while P6 appreciated being able to see the physical environment, contributing to their comfort and sense of presence

Iteration 2 MR:

All participants appreciated the room-scale navigation. P12 stated it was more convincing than expected. P13 and P15 noted it felt natural. P14 said it was fun, and P16 reported that it improved the experience. None reported cybersickness.

Q4: Did the tasks you performed make you feel actively involved in the learning process?

Iteration 1 VR:
P1 felt somewhat involved but noted a lack of feedback which reduced their clarity on tasks. P2 strongly supported the idea of learning by doing and felt very engaged. P3 performed the tasks but admitted to low motivation and a preference for finishing quickly rather than engaging deeply.

Iteration 2 VR:
All five participants (P7–P11) reported that the tasks felt engaging and contributed to an active learning experience. P7 acknowledged learning through physical actions but noted occasional frustration with understanding what to do, preferring action over reading. P8 emphasized that doing the tasks was more impactful than watching someone else, while P9 noted that the interactive format was more enjoyable and educational than a video. P10 described feeling engaged and active during the session, and P11 directly affirmed that the experience was engaging. Across all participants, there was a strong preference for experiential learning through task performance rather than passive observation.

Iteration 1 MR:
All participants reported feeling engaged. P4 felt involved but limited by the simplicity and language barrier. P5 and P6 felt that physical tasks helped them participate more meaningfully and retain the learning content.

Iteration 2 MR:
All participants reported being actively engaged. P12 and P16 linked physical involvement with memory retention. P13 appreciated the balance of reading and task clarity. P14 and P15 felt that the experience made learning enjoyable and more effective.

Q5: Would you say that learning by interacting using "hand tracking and being able to physically move around/controllers and being stationary" is a way to make the content more memorable for you?

Iteration 1 VR:

P1 believed repetition would help memory retention. P2 supported the approach as an effective educational method. P3 preferred hand tracking over controllers and felt that physical interaction would improve memory more than stationary VR.

Iteration 2 VR:
Participant 7 appreciated the fun and interactive nature of the VR experience, especially in a museum context, but noted that for workplace learning, watching a video might be more appropriate. Participant 8 affirmed that learning by doing helped them retain content more effectively. Participant 9 suggested that the experience would have been more memorable if they could physically walk and use their hands instead of relying on controller-based movement, reflecting a desire for more immersive interaction. Participant 10 favored this method of learning, noting that clarity in task instructions enhanced memory. In contrast, Participant 11 acknowledged the effectiveness of the method but preferred a video alternative due to motion sickness.

Iteration 1 MR:
P4 wanted deeper content and clearer language due to the language barrier, while P5 acknowledged its benefit for museum settings but prefers traditional methods for school. P6 found the physical interactivity effective but suggested tasks be broken down to multiple smaller and more clearly defined tasks.

Iteration 2 MR:
All participants preferred learning through physical interaction. P12 and P16 specifically favored room scanning and MR over traditional formats. P14 described MR as a new learning paradigm. P13 saw it as valuable in professional contexts.

Q6: Do you think MR technologies, like spatial scanning and hand tracking/controllers and stationary, can have a positive impact on museum education and improve the way you learn? Why or why not?

Iteration 1 VR:
All participants agreed on the positive potential. P1 emphasized that structure is key for meaningful learning. P2 was very optimistic and highlighted the educational possibilities. P3 saw strong potential for immersive education in museums.

Iteration 2 VR:
Participants generally viewed virtual reality (VR) as a valuable tool for en-

hancing museum education, especially due to its engaging and novel nature. Participant 7 expressed skepticism about the depth of learning VR could offer, describing it as more 'fun than educational.' Participant 8 confirmed VR's usefulness for learning, while Participant 9 raised concerns about accessibility for older demographics. Participant 10 highlighted its engaging nature, and Participant 11 saw VR as a novel and memorable educational tool, though its effectiveness would depend on how it is implemented.

Iteration 1 MR:
All participants acknowledged the potential of MR in enhancing museum learning. P5 and P6 were confident about its effectiveness, while P4 expressed only cautious optimism, suggesting it may work well in theory.

Iteration 2 MR:
All participants responded affirmatively. P12 and P14 emphasized MR's appeal to younger audiences and its memorability. P13 and P15 saw it as more engaging than passive media. P16 saw MR as practical for education, though noted scale and cost limitations.

Q17: Is there anything that was lacking in the experience that you would change or improve?

Iteration 1 VR:
P1 suggested clearer task indicators and better interaction feedback. P2 wanted more concise tasks with start indicators. P3 requested more detailed instructions, improved controller onboarding, and respawning for lost objects.

Iteration 2 VR:
P7 felt overwhelmed by simultaneous audio and text, indicating an overload of information during task execution. P8 suggested implementing an inventory system due to easily lost objects and confusion around interface elements such as buttons. P9 wanted a persistent task and control interface visible throughout the experience to minimize confusion. P10 highlighted the difficulty in handling controllers and proposed a visual controller tutorial at the start. P11 appreciated the current structure but recommended additional feedback mechanisms in the contamination task and praised the realistic visuals seen through windows.

Iteration 1 MR:
Participants pointed to usability and performance issues. P4 found the presser too complex. P5 suggested refining the lock mechanism. P6 reported disap-

pearing objects and recommended adding a respawn feature.

Iteration 2 MR:

Participants offered several suggestions: spreading out info screen text (P12), better hand tracking (P16), more interaction options (P15), and improved voiceover (P14). UI-related suggestions included placing tutorial access in the menu (P15) and improving feedback if the user struggles too long (P13).

Q18: Do you have any other comments or ideas you would like to add?

Iteration 1 VR:

P1 requested always-visible task UI, shorter tasks, and better interaction comfort. P2 appreciated the interaction design of the plant and box. P3 felt overwhelmed by automatic audio at the start and wanted more navigational help like arrows or visual cues.

Iteration 2 VR:

Participants provided a range of suggestions and comments aimed at improving the educational value of the VR experience. P7 highlighted that while the experience was fun, it felt more suitable for first-time VR users rather than for deep learning. P8 noted that the environment felt somewhat empty, suggesting the need for richer visuals or content. P9 emphasized the importance of clearer interaction guidance and mentioned needing help at times, which was mitigated by the task overview tablet. P10 expressed a desire for greater interactivity and more intuitive object manipulation, especially with manual doors. P11 had no additional comments to add.

Iteration 1 MR:

Feedback included praise for the experience and recurring frustration over the presser and objects falling through the floor.

Iteration 2 MR: Participants expressed overall satisfaction. P12 and P15 viewed the prototype as viable for museums and schools. P13 and P14 found it cool and appreciated not having to read everything in the info screens in order to progress.

5.2.2 Design changes based on iteration one feedback

Following the iterative process established earlier in development, user feedback from iteration one of both the VR and MR prototypes played a critical role in guiding subsequent refinements. Grounded in the human-centered design methodology [17], this approach ensured that updates were not speculative but directly informed by real user interactions, preferences, and observed challenges.

As seen in the summary of findings in section 5.2.1, participants reported issues related to interaction clarity, particularly with the plant presser, limited task feedback, occasional performance stuttering, and confusion caused by missing or easily overlooked instructional cues. These insights directly informed a series of design changes aimed at improving user guidance, technical performance, and the overall coherence of the experience in iteration two.

Furthermore, due to the MR prototype's longer development timeline, many findings from the VR prototype's first and second iterations were proactively integrated into the MR version. While both prototypes maintained the same core learning objectives and procedural structure, the MR experience benefited from more advanced refinements, particularly in interaction design, UI feedback, and tutorial implementation.

Framerate optimization

Participants in iteration one occasionally reported noticeable stuttering and performance issues, particularly in the VR prototype during more resource-intensive scenes. To improve the smoothness of the experience, essential for maintaining presence in immersive environments, significant optimization efforts were carried out. These included reducing draw calls, improving asset batching, minimizing unnecessary real-time lighting, and simplifying complex object meshes. Additionally, occlusion culling was implemented in the VR prototype to improve rendering efficiency in enclosed virtual environments. While similar techniques were applied to the MR prototype, occlusion culling was deemed unnecessary due to the performance stability observed during MR testing. As a result, iteration two exhibited more consistent framerates, with fewer reported disruptions, allowing participants to remain focused and immersed in the learning experience.

Tutorial

To reduce early confusion and help users become familiar with the interaction methods, tutorials were introduced in both prototypes. The VR version included a brief tutorial screen covering controller use, while the MR prototype featured a more immersive tutorial area in the reception space, guiding users through hand tracking and spatial navigation. This change was informed by iteration one findings, where users (e.g., P1 and P2 in VR) expressed uncertainty about controls and task expectations. The tutorial aligns with educational design principles such as scaffolded learning and Mayer's Multimedia Principle, by easing users into the experience and reducing cognitive load. It also supports embodied learning, giving users a chance to physically practice interactions before performing the actual tasks.

Dividing tasks into smaller, clearer segments

One of the most influential design changes implemented after the first round of user testing was the division of tasks into smaller, clearer segments. This adjustment was made to both the VR and MR prototypes, with the MR prototype segmenting the tasks even further to support better cognitive flow and user understanding. In VR iteration one, several participants expressed confusion about what they were expected to do next, particularly during multi-step interactions such as the plant pressing or DNA testing tasks. This was reflected in the MR iteration one observations, where users like P1 and P3 struggled with understanding the sequence of actions within the pressing room and required repeated guidance. By breaking down complex procedures into more manageable sub-tasks, the researchers aimed to reduce mental overload and improve user confidence. This change was validated during VR iteration two, where users showed smoother progression and fewer requests for help, indicating that the clearer task structure supported better orientation and engagement. The MR prototype benefited particularly from this iterative insight, as the task structure was refined with even greater granularity to ensure intuitive progression in a more physically interactive environment.

Task overview menu

Another significant design change was the replacement of static info screen spheres with a dynamic, user-activated menu system. In the first iteration, interactive spheres were placed above each info screen, allowing users to toggle between the task list, instructional videos, and general information about the learning objectives in the space. However, this design was ultimately ineffective as almost all users overlooked the spheres entirely, leading to confusion and under utilization of the support material. Additionally, the spheres introduced visual clutter and provided limited flexibility in how users accessed information. In response to this, the spheres were removed in favor of a centralized menu screen that users could open at any time. The updated menu presented concise task guidance and instructional content on demand, promoting user autonomy and reducing dependency on environmental triggers.

Persistent UI notification panel

A new static UI notification panel was introduced in the top-right corner of the user's field of view in the MR prototype. This element provided a concise summary of the current task, accompanied by a menu icon indicating that more detailed instructions could be accessed at any time through the menu system. This design change was directly inspired by feedback from iteration one of the VR prototype, where several participants, particularly P1 and P2, expressed uncertainty about what to do next and often forgot the sequence of actions required. In some cases, users were unaware that they could revisit instructions, leading to repeated interruptions and guidance from the researchers. By implementing a persistent task panel in the MR prototype, users received a continuous visual reminder of their objectives, reducing confusion and enabling more independent task navigation.

Plant presser

Early usability testing across both VR and MR iterations revealed that several participants found the plant presser unintuitive and confusing to operate. In particular, findings from VR iteration one and MR iteration one highlighted issues with understanding the presser's lock mechanism and lack of clear feedback during interaction. To address this, multiple visual UI icons were added directly to the presser in the MR prototype to improve interaction clarity. These included animated indicators and feedback cues that guided users step-by-step. Furthermore, the presser was incorporated into the MR prototype's tutorial section, allowing users to freely interact with it while receiving guidance through instructional text and video demonstrations.

Task completion chime

A task completion chime was added to both prototypes as a form of immediate, unobtrusive feedback to signal when a task had been successfully completed. This design decision was based on feedback from earlier iterations, particularly in VR iteration one and two where users sometimes expressed the need for structural feedback. In line with the guideline 'Give players unobtrusive, immediate, and actionable feedback' (Section 4.2), the chime also served to reinforce progress without disrupting immersion. Combined with the persistent task UI panel, the audio cue aimed to provide users with a clear sense of advancement.

Bug fixes and improved interaction stability

Critical bugs encountered in iteration one disrupted task flow and may have impacted user immersion, negatively affecting the user experience. In response fo iteration 2, several technical fixes were implemented, including object respawning mechanisms and collision boundary adjustments, to prevent game-breaking issues. As a result, iteration 2 demonstrated significantly greater technical stability, allowing users to complete tasks with minimal external intervention

5.2.3 Understanding the influence of user interaction modalities on presence & engagement based on findings

Based on the findings from qualitative interviews and quantitative questionnaires, a thematic analysis was conducted for both iterations within both prototypes. As a result, diverse themes and sub-themes were identified and addressed in the following section to interpret how the different user interaction modalities have influenced the user's perceived level of presence and engagement.

Intuitive interaction and engagement

One of the most evident distinctions between the MR and VR experiences was how users perceived the intuitiveness of their respective interaction modalities, and how this reflected how engaged they felt during the experience. Across both post-test interviews and questionnaires (Appendices K - N) , participants in the MR prototype consistently reported that using their hands to interact with the environment felt more natural, fluid and intuitive. For example, in iteration 2 of the MR prototype, 100% of participants either agreed or strongly agreed that hand tracking felt intuitive, and all participants felt the environment responded naturally to their actions. P12 described hand-based interaction as 'surprisingly responsive', while P13 and P14 emphasized how intuitive it felt compared to using traditional controllers due to previous experiences.

In contrast, while the VR prototype also received some positive feedback on engagement, the findings reveal more mixed perceptions of controller intuitiveness. In iteration 2 VR, two participants described that using the controllers to interact with the environment did not feel natural, where there were challenges in adapting to the controller inputs even though the users were helped by the researchers. This may not exactly reflect badly on design principle 1 [22] - Assume every learner is a VR beginner, as many novice players struggle to adapt to the use of controllers. P7 and P8 mentioned struggling to interpret certain button inputs, and P10 expressed a desire for a more physical interaction method, reflecting kinesthetic learning preferences mentioned in chapter 2. Although some participants eventually adapted, the learning curve, especially in iteration 1 where no tutorial was provided, was noted as a barrier to engagement. Therefore, the fact that the interactions felt less 'natural' for diverse users may have influenced their sense of immersion and presence in the environments leading to less engagement. Further, the MR's hand-based interactions naturalness may have promoted a more immediate sense of embodiment among participants and also managed to reduce the cognitive effort needed to learn the controls, allowing participants to focus more on the learning activities rather than using their energy on constantly trying to understand the controls.

Influence of movement freedom on presence

A major noted theme was that the freedom of physical movement played a fundamental role in the user's perceived level of presence across the two prototypes. In the MR experience, participants frequently described feeling more immersed and in control of their actions. Quantitative data shown in Appendices K - N consistently supported this, with all participants in iteration 2 stating that physically moving around the space felt very natural. Similarly, participants strongly agreed that the environment responded to their actions and that physically interacting with the scanned space enhanced their feeling of embodiment, meaning their connection with the environment and interactions [84]. P16 described spatial scanning movement as 'improving the experience', while P14 stated that it made the experience feel 'fun' and 'more real'. No participants in the MR prototype across iterations experienced cybersickness which was something very positive in comparison to the VR experience, and the alignment between physical and virtual space contributed to a strong feeling of presence.

On the other hand, as the VR prototype required users to remain stationary and navigate using teleportation, it led to more mixed reactions. While teleportation allowed users to explore a larger virtual area of the museum's herbarium, it also disrupted the embodied flow of movement for some participants. In iteration 2 VR, P10 stated they felt discomfort being stationary, even joking that they 'needed a seatbelt' due to the mismatch between wanting to move physically and the system's constraints. This reflects once again the fact that learners simply have different learning preferences, whereas kinesthetic learning seems to allow users to become more engaged and present within the experience. P7 and P11 similarly described issues with rotating with the controllers. Although some participants like P9 found teleportation preferable to continuous movement due to previous experiences, these findings suggest that limited movement made the interaction feel less natural and reduced the sense of presence for some participants within the VR experience. This is further seen in the questionnaires, seen in Appendices K - N , where responses were divided on whether teleportation and stationary navigation felt intuitive or immersive among both iterations.

Overall, it is evident that the MR prototype's ability for physical locomotion appeared to offer a stronger contribution to spatial presence as well as engagement which confirms **hypothesis 3**. This possibility of moving naturally to interact with the virtual elements onto the real physical world reinforced the illusion of 'being there' and allowing participants to feel more embodied within the environment, where in contrast to the artificial movement in VR occasionally created a disconnect between action and perception. Through the observations as well as qualitative interviews, participants did not comment negatively on the fact that the mixed reality experience is a mix of the real world and the digital world. The fact that users could walk around and use their hands, this perception of the real world physical objects did not reduce the immersion participants were feeling. Due to this, it became evident that **hypothesis 1** has been confirmed as users did not feel that this diminished their experience.

Embodiment and sense of control

The sense of embodiment, meaning the feeling that one's physical presence and actions are reflected within an immersive environment, was directly influenced by the interaction modalities in diverse ways. In the MR prototype, participants generally reported a heightened sense of being 'in the environment', closely connected to being able to use their real hands instead of controllers.

This was evident in post-test interviews. For example, P15 stated that 'using my hands made it feel like i was actually there doing it', and P14 described the experience as 'a new kind of learning where you're not just seeing, but physically part of it'. Unlike the more general intuitive engagement discussed previously, these statements reflect how physical self-representation and direct manipulation translated into a deeper connection with the environment.

Participants in the VR prototype, however, expressed varying levels of control. While some managed to adapt to the controllers, other reported moments of misalignment or awkwardness that reduced their sense of agency. P11 described the need to stand up unexpectedly due to height calibration issues, creating therefore a disruption in their presence and embodied experience. Others like P9 mentioned difficulties with controller-based object manipulation, which occasionally broke the illusion of being in control of their actions. The fact that the controller interactions relied on indirect and limited gestures, it may have added a cognitive layer that reduced the sense of physical integration. These differences were reflected in the questionnaire results, seen in Appendices K -

N , as MR participants strongly agreed that the environment responded clearly to their actions and that they felt physically present, while VR participants' responses were more mixed. Fewer VR participants agreed that their hand representation or the interaction model made them feel physically involved, suggesting a weaker embodiment effect. This can be due to the fact that since many were novice learners, their experience would have benefited of seeing an actual representation of the controllers instead of their hands, being therefore able to see the controls.

Break in presence: Frustrations and disconnect

While both VR and MR prototypes aimed to foster immersive and engaging environments, several participants across both modalities experienced breaks in presence such as moments where technical limitations, interaction issues, or confusing task design disrupted their sense of being in the environment.

These breaks happened mostly in the VR prototype, especially in iteration 1 and partially in iteration 2. Many participants reported issues such as cybersickness, awkward controller calibration, and bugs that affected object interaction. For example, P3 in iteration 1 VR described being overwhelmed and preferring to finish quickly due to low motivation and discomfort. P1 experienced 'shaky visuals' that contributed to confusion and mild cybersickness, while P9 in iteration 2 VR mentioned a critical error that broke their immersion mid-task. Comments like P11's feedback about needing to stand due to incorrect virtual height alignment also reflected mismatches between the virtual body and the real body that disrupted embodied presence.

On the other hand, the MR prototype generally maintained presence more effectively, though it was not without occasional challenges. Technical issues such as hand tracking bugs, as reported by P16 in iteration 2 MR, and a non-intuitive press-lock mechanism within the plant presser, iteration 1 MR, were noted. However, these rarely increased into full breaks in presence. Instead, participants often adapted or continued exploring without losing focus. This may be due to the naturalness of the experience, while in VR, users are more restricted to one position and may therefore affect how they perceive and engage with the content. P14 and P16, for instance, demonstrated strong engagement and even verbally expressed excitement during the tasks, such as saying 'this is cool' and 'damn,' despite minor issues.

These qualitative findings were further reinforced by the quantitative data shown in Appendices K - N. as VR participants showed more neutral or disagreeing responses on presence, related questions such as 'I felt present in the environment' and 'I was not easily distracted by the interface or controls.' In contrary, MR participants overwhelmingly agreed with presence-related statements, suggesting fewer interruptions in their immersive experience. Overall, breaks in presence were more frequent and more disruptive in the VR prototype, often caused by the controller limitations, environmental misalignments, and bugs that impacted task performance. The MR prototype, despite occasional technical issues, preserved a more continuous sense of presence due to its more natural interaction model and spatial alignment.

5.3 RQ3 - How do the different user interaction modalities affect memory retention after using the immersive experiences?

5.3.1 Summary of findings from user tests: iteration one and two

In this study, memory retention was measured as an indicator of short-term memory through post-test questionnaires and follow-up interviews conducted immediately after the immersive experience. It is important to note that some questions present in iteration two were not included in iteration one due to iteration refinements and additions made based on feedback and insights gathered during the first iteration.

Questionnaire findings in iteration one & two

All questionnaire findings from both iterations within both prototypes can be seen in Appendices K - N .

Oral recall post-test interview

Q7: Could you walk me through the steps or processes you remember before entering the herbarium lab in the MR/VR experience? What stood out to you?

Iteration 1 VR:

P1 recalled needing protective clothing. P2 remembered the reception area and elevator, but not the outfit. P3 described the sequence correctly, including using the keycard, elevator, and button.

Iteration 2 VR:

Participants generally demonstrated good memory retention for the initial sequence of actions leading to the herbarium lab. All five participants (P7–P11) mentioned retrieving the keycard and using it in the elevator, with minor variations in how much of the sequence they recalled. Participant 9 showed strong attention to detail, including auditory cues such as the voiceover. Others, like P10 and P11, remembered the order of locations and interactions, including controller tutorials.

Iteration 1 MR:

All three participants recalled the need to wear protective clothing. P4 and P6 remembered specific elements and gave reasons such as contamination prevention. P4 also mentioned putting on clothes but mixed it with an unrelated task.

Iteration 2 MR:

Most participants recalled equipping lab clothes from the wardrobe and using the tutorial section (P12, P13, P14). P15 recalled gloves and shoes. P16 misremembered the sequence slightly, mentioning the elevator and preparing the plant first.

Q8: Can you recall one of the tasks you performed? What details do you remember about that task?

Iteration 1 VR:

P1 gave a complete sequence from collecting the plant to completing the DNA test. P2 recalled equpping protective gear and using tweezers during the DNA test. P3 remembered steps involving the DNA test and setting the correct temperature at the end.

Iteration 2 VR:

P7 recalled multiple steps including pressing, boxing, using the lab, and archiving the plant, showing a clear sequential memory. P8 gave a detailed account from plant preparation to temperature adjustment, reflecting strong procedural memory. P9 remembered key steps like using the presser and the dryer but questioned the rationale behind some actions, such as the logic of DNA sampling. P10 associated physical action with memory, emphasizing the benefit of interaction. P11 demonstrated high task retention and even reported learning something new - that the flowers of the plant can, but should not be used for DNA testing.

Iteration 1 MR:

P5 and P6 accurately recalled sequential steps for tasks like pressing a plant and conducting DNA tests. P4 could not recall the process due to a glitch, suggesting technical stability is key for memory retention.

Iteration 2 MR:
Most participants described the plant pressing or DNA testing process in detail (P12, P13, P14, P15, P16). Their responses included steps like using tweezers, drying plants, and archiving.

Q9: Do you remember why certain procedures, like using protective gear, drying a pressed plant or regulating the temperature, were important in the context of the tasks? Can you explain why they matter?

Iteration 1 VR:
P1 vaguely recalled the importance of contamination prevention but admitted to not reading much. P2 had a solid understanding of the procedures. P3 did not remember why the procedures mattered.

Iteration 2 VR:
Participant responses varied in how well they recalled the reasoning behind specific procedures. P7 remembered the urgency of the temperature issue, noting that the pressure of the moment made it more memorable. P8 correctly recalled the purpose of lab coats to prevent contamination and the need for archival structure. P9 initially forgot the reasons but was able to explain the purpose once reminded. P10 focused more on the interaction itself and did not retain much of the underlying theory. P11 did not recall the contamination-related reasoning at all.

Iteration 1 MR:
P5 and P6 understood the need for contamination prevention and plant preservation. P4 relied on prior knowledge and had difficulty accessing Norwegian-language content.

Iteration 2 MR:
Most participants accurately recalled reasons for contamination prevention (P12, P15, P16). Some gave partial or incorrect reasoning (P13, P14).

Q10: Do you remember the name of the plant that you worked with in the experience?

Iteration 2 VR:

Most participants were unable to recall the plant name used during the experience. P10 partially remembered the first part of the plant's name, while P7, P8, P9, and P11 could not recall the name at all.

Iteration 2 MR:
None of the participants remembered the full name. P14 and P16 remembered parts of it such as 'moris,' 'mor').

Q11: Do you remember where you had to archive the plant and why it's important to archive the plants in a specific structure?

Iteration 2 VR:
All five participants were able to recall the correct archiving location—shelf number 2, indicating retention of procedural steps. However, four of the participants (P7, P8, P10, P11) could not recall or explain why archiving in a specific structure was important, while only P9 connected the archiving to aiding other researchers through organization. This shows that while the task itself was remembered, the reasoning behind it was less well retained, possibly due to the emphasis on action over conceptual explanation during the experience.

Iteration 2 MR:
All participants recalled archive row number 2. However, most were unclear or incorrect about the purpose of archiving, with only P13 and P12 referencing organization.

Q12: Do you remember what information you got out of the DNA test?

Iteration 2 VR:
Participants showed mixed levels of recall when it came to the content of the DNA test results. P7 remembered that the DNA test provided the archive number but did not recall the other available information. P8 reported no memory of the DNA test details. P9 recalled partial information, such as plant characteristics and a vague reference to geography (e.g., "America"), though the recall lacked specificity. P10 provided the most accurate response, remembering that the test displayed the plant's genetic code and its characteristics, though not in complete detail. P11 admitted to not reading the screen at all, prioritizing action over textual content.

Iteration 2 MR:
P12 remembered plant height. P14 and P16 recalled archive location and plant

image. P13 skipped reading. P15 vaguely recalled habitat information

Q13: What was the minimum and the maximum optimal temperature to store the plants?

Iteration 2 VR:
Participants displayed varying levels of retention regarding the optimal storage temperature. P8, P10, and P11 accurately remembered the correct range of 18–20 degrees Celsius. P7 recalled only the upper limit ('20'), showing partial recall. P9 did not provide an answer, stating the topic was uninteresting and choosing not to engage with the question. These differences suggest that while some participants retained factual content well, others either lacked interest or were not engaged deeply enough to retain exact numerical data.

Iteration 2 MR:
P12, P14, and P16 correctly answered 18–20°C. P15 remembered only 20. P13 answered incorrectly.

Q14: Were there any facts or pieces of information that stood out to you during the experience? If yes, what were they?

Iteration 2 VR:
Participants reflected on a variety of details that stood out during the VR experience. P7 highlighted the full process of preparing the plant, including locking, pressing, and storing. P8 specifically remembered the contamination procedure as a key point. P9 was impressed by the visual aesthetics of the laboratory environment. P10 expressed disinterest in the info screens, preferring other types of content delivery. Meanwhile, P11 appreciated the realism of the experience, mentioning gravity, the realistic environment, and the fun of interacting with spray bottles.

Iteration 1 MR:
Participants recalled different types of information. P5 remembered scientific facts, P6 noted environmental objects like the trolley, and P4 remembered frustrating the presser and the alarm audio.

Iteration 2 MR:
Participants highlighted different elements: P12 liked the lab design and balance of challenge. P13 appreciated UI feedback. P14 and P16 mentioned the elevator and temperature room, respectively. P15 praised the overall layout and wardrobe room details.

Q15: Did physically performing the tasks yourself rather than simply observing or reading about them, help you remember the information more effectively? Please explain why or why not.

Iteration 1 VR:
All participants agreed that active participation enhanced memory. P1 and P2 emphasized that physical interaction made learning more effective, while P3 highlighted the role of visualization and performing tasks in improving understanding.

Iteration 2 VR:
Participants generally agreed that active engagement through physical interaction helped enhance memory retention. P7 provided a nuanced perspective, stating that while they remembered what they did, they didn't always understand why they did it. P8 specifically recalled that the pressing task felt significant, suggesting a deeper level of involvement. P9 strongly affirmed that performing the tasks was more effective than passively watching a video, and P10 emphasized remembering the structure of the tasks due to the embodied nature of the activity. P11 also agreed, stating they wouldn't have thought as much about the process if they had only observed it.

Iteration 1 MR:
P5 and P6 affirmed that physical interaction helped them remember. P4 preferred traditional learning methods but acknowledged some benefit to doing.

Iteration 2 MR:
All participants agreed that performing the tasks themselves was more effective than passive methods. P12, P13, and P16 emphasized doing over reading. P14 and P15 noted it made the experience more memorable and practical.

5.3.2 Understanding the influence of user interaction modalities on memory retention based on findings

To explore how the different interaction modalities affected participant's memory retention, this section reflects and interprets the findings from qualitative interviews and questionnaires conducted after experiencing both the VR and MR prototypes across iterations. Participants were asked to recall tasks, procedures, and factual information encountered during the experience, and to reflect on whether physically performing the tasks helped them remember better. Participant's responses revealed patterns in how the different interaction modalities shaped their ability to retain procedural steps and conceptual understanding. Through a thematic analysis, themes and sub-themes were identified, each shedding light on different aspects of how the different user interaction modalities may have influenced memory retention in the immersive experiences.

Learning by doing

Across both the VR and MR prototypes, one of the most consistent patterns observed was that participants attributed their ability to remember tasks and procedures to being actively engaged during the experience. This was highlighted in both controller-based and hand-based interactions. As conceptualized in chapter 2, this pattern aligns closely with the principles of embodied cognition [84] and experiential learning [26], which suggests that learning by doing through physical interaction and engagement is a way to enhance memory as well conceptual understanding.

In the post-test memory recall interview, nearly all participants across both iterations within both prototypes stated that performing the tasks themselves was more effective than if they passively had to read or observe. For example, P10 in VR iteration 2 VR stated that physically completing the tasks helped them remember the structure of the experience, while P15 in MR iteration 2 noted that performing the procedures made the experience feel more ’practical and memorable’ due to the hands-on nature. Similarly, P9 in iteration 2 VR emphasized that they would not have remembered the steps as clearly through observation alone, and P13 in iteration 2 MR described that ’doing’ helped more than it would most likely have been by simply ’reading’.

Additionally, this tendency was also reflected in the quantitative questionnaire responses, seen in Appendices K - N , where participants overwhelmingly agreed that tasks and interactions helped them remember what they learned. All participants in iteration 2 MR believe they retained more information through this experience than they would have by reading or watching a video. 100% of participants in iteration 1 MR indicated that the tasks and interactions made it easier to retain information. The results were consistent throughout iteration 2 as well where participants both agreed and strongly agreed. Additionally, all MR participants strongly agreed or simply agreed that they could confidently explain the procedures they performed, apart from one participant who responded neutral, suggesting a direct connection between physical interaction, involving hand-based interactions and movement, and procedural memory retention. Moreover the ability to use hands as a way of interaction also received strongly agreements where most participants answered strongly agree and agree on 'Being able to use my hands to interact in the environment positively had an impact on my ability to learn and retain information'.

In comparison, the controller-based interactions in the VR prototype also demonstrated positive outcomes where all participants felt involved and recalled an extended amount of information. Participants like P8 in iteration 2 VR described remembering detailed sequences of actions, including pressing and archiving plants, highlighting that even non-gesture-based user interaction modalities can support memory retention if well-structured and meaningful. However, there was some mixed feedback in iteration 2 VR regarding how controller-based interactions supported structured and easy-to-follow learning. Two out of five participants disagreed that the controller-based tasks were easy to follow. This might not directly reflect that the interaction modality was the problem, but rather the structure of the tasks through the visual cues and feedback.

Overall, the findings suggest that active engagement through interaction, whether via hand-based or controller-based interaction, played a fundamental role in reinforcing procedural memory. The physical involvement of the learning experience not only enhanced participants' attention but also helped them describe steps, sequences, as well as the logic and structure of the tasks they performed. Nevertheless, the MR prototype suggested slightly stronger outcomes in terms of user confidence, procedural recall, and perceived learning impact. This suggests that more natural and embodied interaction modalities may have a modest advantage in supporting memory retention, especially when supported by intuitive and clear task structure.

Limited body movement in VR may reduce retention compared to MR

An influential theme that emerged throughout data analysis was that limited physical movement within the VR environment may have influenced the depth of memory retention compared to the MR experience. While both prototypes involved structured task-based learning, the VR setup relied on stationary controller-based interactions using teleportation as a way of navigation. This restricted the user's physical involvement to seated or minimal standing engagement. In contrast, the MR prototype allowed users to walk around a spatially scanned environment and use their hands to interact directly with objects, fostering therefore a more kinesthetic and embodied experience.

There were several participants in the VR group that demonstrated good recall of task sequences, however struggling more with understanding the reasoning behind them. This pattern aligns well with another identified theme that will be further elaborated in this section, namely 'remembering what they did, but not necessarily why they did it'. For example, P11 in iteration 2 VR could recall what actions were done but not why they were important, and P9 stated that while they remembered performing a task, they did not fully understand the rationale behind it such as the logic of the DNA test. This difference between procedural memory and conceptual understanding may be due to the limited body movement that VR participants had, reducing therefore opportunities for a deeper cognitive engagement with the experience. Furthermore, as mentioned, the MR prototype allowed users to physically walk around, allowing for a stronger sense of agency and embodiment with the environment. Questionnaire responses, seen in Appendices K - N , reinforce this difference: the statement 'Being able to physically move around positively had an impact on my ability to learn or retain information' received strong agreement in the MR prototype. Meanwhile, in the VR prototype, the statement 'Being in a stationary position did not negatively impact my ability to learn or retain information' received mixed responses. Some participants agree that the stationary setting did not hinder their learning, however others, such as P1, P3, and P11 reflected in interviews that the experience felt less memorable or that certain details were more difficult to remember. This reflects some uncertainty regarding **hypothesis 2**, as most participants in iteration 2 VR were neutral regarding this statement. P7, for instance mentioned that even though it was VR, it was expected to go physically which made it 'weird' using teleportation at first. VR may contribute to a better memory retention as users are fully immersed in a fully virtual environment. However, in this case due to factors such as teleporation restriction and other factors, it may have deviated some users from the educational goals and negatively impacted their memory recall.

Additionally, MR participants particularly in iteration 2, showed efficient task recall and a stronger understanding of the contextual meaning. P12, P13 and P15 were not only able to remember the steps but also described why procedures like wearing protective clothing or archiving in a structured way was important. This may be due to the increased physicality and realism of the MR prototype, where there is more body involvement and also the fact that spatial exploration closely replicated real-life procedures due to hand-gestures in comparison to using the controllers.

This pattern became also quite evident in the questionnaires, seen in Appendices K - N . MR participants in both iterations strongly agreed with statements such as 'The tasks and interactions helped me remember what I learned' and reported higher perceived immersion as well as realism. Although mostly all participants in the VR prototype also reflected that the tasks and interactions made it easier to remember what they had learned, this was not well reflected during the interviews. This might suggest the idea that physical movement through the environment as well as full-body interactions can allow for a deeper learning with the content where multiple sensory channels are engaged, further supporting kinesthetic preferences for learning. This reflects similar insights from Rey's et al. [54] study in chapter 2, who found that room-scale navigation led to better memory outcomes than teleportation, although it introduced higher cognitive load. For this specific user case scenario, the herbarium MR experience's greater physical involvement seems to have supported memory retention without overwhelming users as no participants described any form of overwhelm throughout the experience. In contrast to a more restricted VR setup, the MR prototype allowed participants to engage more naturally with the tasks, which may have been one of the reasons behind them remembering the learning content more effectively.

Learning curve with the controllers can have an impact on the learning experience and retention

The learning curve participants, particularly with VR, ended up being a constant pattern reflecting that it may have influenced retention in the immersive experience. Here, it was also reflected regarding at a post-test interview question shown in findings of RQ2: 'How did you feel about using the controllers/hands as a way of interaction in the experience?'. The ease or difficulty of adapting to an interaction modality can be an influential factor regarding the user's ability to engage with, and ultimately retain educational content. One of the biggest issues with iteration 1 both in the VR and Mr prototypes was the lack of structured onboarding tutorials, which was also a highly identified pattern, leading to diverse observable challenges during testing. In the VR experience, participants such as P1 and P10 expressed confusion about how to operate the controllers, stating that it took some time to understand and remember which buttons to use and that they would have liked to see the controller layout in VR during the experience, instead of a visualization of virtual hands. This initial barrier to interaction may have been an influential factor that diverted cognitive focus away from the learning content, possibly affecting retention outcomes.

In contrast, iteration 2 introduced tutorials tailored to each prototype's interaction modality. In the VR prototype, a visual layout of the controllers was introduced at the beginning. In the MR prototype, a physical tutorial space allowed participants to familiarize themselves with hand gestures such as grabbing, poking, and pinching. Although this was an improvement in the VR prototype and now illustrated controllers to users, P10 as mentioned still struggled and expressed confusion mentioning that it was 'difficult to know which hand i was supposed to use'. This means that a physical tutorial in the VR was required, like it was implemented in the MR. This may have been a factor to why there were diverse mixed responses regarding 'The controller-based interactions made the learning tasks feel structured and easy to follow' were two participants disagreed and strongly disagreed. In contrary, this improved guidance helped some participants feel more prepared and confident before beginning the actual tasks such as P8 and P13. They noted that the tutorials made it easier to understand the interactions, allowing them to focus more on the content and tasks.

Despite the added tutorials, the learning curve was still apparent for some, mostly in the VR prototype. P7 mentioned that it took a little bit of time to get used to it, but got used to it with time. P7 further emphasized that it was challenging to understand what the different buttons did in the tutorial screen when there was not visualization of the actual controller buttons, however P7 still enjoyed seeing a visualization of virtual hands. P8 furthermore understood the controllers once familiar with them by looking at the tutorial screen. This showed successful learning, suggesting that controller inputs can still be effective with light onboarding. In contrast, even though having the tutorial available, P11 found it very confusing and not intuitive. The participant found the controllers were difficult and confusing to use. P9 in VR felt it was fine, however this was due to previous familiarity with the technology. This learning curve could be one of the reasons two participants disagreed in the questionnaire regarding that they did not feel confident they could explain the procedures performed during the experience.

Comparing directly to the MR prototype iteration 2, the results were highly positive regarding hand-based interactions. The combination with audio feedback also reinforced this as P12 emphasized. P13 had previously used controllers in other scenarios of use and expressed a high ease and satisfaction using hand-based interactions over traditional inputs. This also applied to novice users, particularly P16 who despite being new to the use of hand tracking, became confident and adapted fast to it. P15 further emphasized that hand use during interactions supported retention. This was a good improvement in relation to iteration 1 MR where there was not physical tutorial. P5 required an explanation but once learned, it felt natural to use. P4 found however hand tracking inconsistent and not particularly helpful for learning engagement. This opinion may however had changed if a tutorial had been available.

These findings reflect the critical role of a structured onboarding in diminishing the cognitive load regarding the learning adaptation to new interaction modalities. The lack of a clear tutorial during iteration 1 led to early confusions, which may have interfered with participants' focus on the educational content. This was mostly in the VR prototype where controller-based interactions were utilized. By iteration 2, the inclusion of tailored tutorials helped alleviate some of the challenges, especially in the MR prototype, where embodied hand-based interaction were quickly adopted, even by novice users. This means that when interaction modalities are introduced with intuitive, hands-on tutorials, users are better able to concentrate on task performance and retain key learning content. In contrast, the poorly explained static controller layout with no real time physical reference, could have been a factor in delaying user adaptation and compromise memory retention. Therefore, regardless of modality, the ease with which users can learn the interaction system significantly influences the effectiveness of immersive learning environments. This means that the VR prototype poorly addressed the design principle 1 named in chapter 4, assuming that every VR learner is a beginner.

Remembers what to do, but not the why

Another pattern noted regarding memory retention was 'remembering what to do, but not the why'. This was specifically referred to the fact that many participants successfully remembered what actions they performed during the herbarium experience, however had difficulties explaining why those actions were necessary. For instance, in the VR iteration 2, although all participants recalled performing the archiving tasks, only P9 could reflect its purpose. Similarly, while most participants remembered equipping the protective gear, only a few like P8 explicitly connected it to the contamination prevention procedure. This could be due to several factors, something highly observed during user testing, such as the fact that many participants skipped the information screens, or simply because many were too focused on still adapting to the controllers and therefore did not have the time and effort to focus on the theoretical information. In some cases, participants were just simply focused on interacting with the environment such as P10 in iteration 2 VR, who mentioned 'I'm more dependent on the interactions and ended up not remembering much of the theory'. Others such as P7 remembered certain procedures because something sudden happened, such as the alarm sound notification to adjust the temperature. In the MR prototype, this pattern was also observed. While procedural steps were generally remembered, the reasoning behind their importance was more limited, with only P12 and P15 recalling the importance of contamination. One specific participant, namely P13, who provided inaccurate reasoning, mentioned the 'need to pay more attention'.

As mentioned, one of the possible reasons for this disconnect could be the focus on interaction modalities and the lack of a more comprehensive tutorial specifically for the VR prototype. As some participants, namely P1, P10 and P11, in the VR prototype reported cognitive effort being directed toward the adaptation of the controllers. This may have left less mental effort for reflecting on the meaning behind each task.

Another contributing factor could be the lack of immediate explanatory feedback during task execution. While users were told what to do next through audio and/or spatial cues, they were not always told why it mattered, unless users actually read or listened to the info screens. During user testing as mentioned, it was observed that many participants skipped or overlooked these screens, not taking with them important theoretical information about the different scenarios. An example was P1 who did not read and simply relied on guessing. The same applied to P10 who focused more on the interactions. As Mayer's cognitive theory of multimedia learning [33] suggests, active learning is most effective when both action and understanding are scaffolded together, which was poorly reflected on some participants. This means that they focused more on what the task was rather than its importance.

These findings reflect that the interaction modalities, particularly those with a higher learning curve such as the controller-based VR during this study, can shift focus toward how to perform tasks, and away from why they matter. The higher conceptual retention in MR may have been due to the fact that the tutorial was more detailed, in comparison to the VR prototype. However, this could have also been simply due to the fact that some participants were more engaged in interacting as seen, rather than reading meaning that the interaction modalities may have not played a big difference regarding conceptual retention.

Chapter 6

Conclusion & future development

6.1 Conclusion

In conclusion, this thesis investigated how emerging interaction modalities in immersive virtual and mixed reality technologies, specifically hand tracking and spatial scanning, can be designed and developed to facilitate active learning by fostering meaningful, memorable, and immersive experiences within educational and museum settings. Two proof-of-concept prototypes were developed to compare traditional VR interactions with MR user interaction modalities: a stationary VR prototype using controller-based interactions, and a MR prototype utilizing hand tracking and spatial scanning. Both prototypes were designed within a herbarium use case, inspired by a collaboration with the Natural History Museum in Kristiansand, where users explored and performed simulated herbarium procedures. Their challenge in making the herbarium accessible to the public made this ideal for the development of immersive solutions and further allowed the researchers to find appropriate research directions regarding the purpose of the study. Guided by a human-centered design (HCD) approach, the development process incorporated educational VR design principles, insights from state-of-the-art research, and requirements validated through preliminary user interviews conducted at the museum. User testing was further conducted through a qualitatively dominant mixed-methods approach, involving 16 participants across four testing sessions in two iterations. Data collection methods included user observations, qualitative interviews, and quantitative questionnaires. The data was then analyzed through a thematic analysis method revealing fundamental insights and patterns in how the different user interaction modalities within both developed prototypes influenced users' perceived presence, engagement, and memory retention.

RQ1 - How can mixed and virtual reality experiences be effectively designed and developed to facilitate active learning in educational and museum environ- ments?, has been addressed through a human-centered design approach where two immersive prototype approaches supporting active learning have been developed within an herbarium use case. It effectiveness was recommended by VR design principles, which were also applied for the MR approach, and were further supported by existing studies The design was guided by VR design principles and informed by theories of embodied cognition and experiential learning, which emphasize the importance of physical interaction and direct experience in promoting a deeper understanding and engagement. While the context of use was museums, the findings revealed that the solutions and its diverse integration of user interaction modalities are effective and can be utilized in the broad educational context, however depending on several factors reflected by user interviews conducted on the target audience: context of use, how interesting the topic is, scenario of use, technology familiarity. Further, design decisions and multimedia elements play a fundamental role in the effectiveness of learning, namely how user interaction modalities are integrated and combined with multimedia elements such as visualization, navigation, audio text which together can provide an immersive and effective active learning experience.

RQ2 - To what extent does hand tracking and spatial scanning influence the users' perceived level of presence and engagement in the mixed reality experience compared to virtual reality interaction methods?, was addressed through conducted user testing with 16 participants across two iterations of the developed VR and MR prototypes to access their perceived level of presence and engagement within the use of the different user interaction modalities within both prototypes. Overall, results were positive across both interaction modalities, however the naturalness of the MR's hand-gesture and physical navigation within the herbarium's activities revealed higher engagement and presence in contrast to the VR prototype. Certain factors such as kinesthetic learning preferences among users who tested the VR prototype revealed this constraint of being stationary and not being able to physically move highly impacted user's sense of presence. Other factors, such as controller learning curves also played a critical role as well as interactions feeling more natural and embodied in the MR experience. Although the VR experience was still considered fun and engaging, this restrain of movement and limited gestures revealed to less engagement and presence in comparison to the MR approach.

RQ3 - How do the different interaction modalities affect memory retention after using the immersive experiences?, was also addressed through the conducted user testing following user testing with the immersive VR and MR prototypes. The findings revealed that the implemented user interaction modalities within the different prototype approaches had a noticeable influence on what participants retained after, reflecting short-term memory retention. Through an in-depth qualitative oral recall interview as well as the completion of questionnaires, participants reflected on their experience and certain tasks and concepts they remembered. While both user interactions supported memory of procedural steps ('what to do'), participants using the MR prototype demonstrated stronger recall of contextual understanding ('why to do it'), likely due to the intuitive and embodied nature of hand tracking and spatial engagement. In contrast, VR participants often remembered the actions but struggled with conceptual depth, potentially due to the cognitive load imposed by the learning curve with the controllers and restriction of being stationary while navigating. These insights highlight how natural, physically grounded interactions in MR may better support meaningful retention in immersive learning contexts.

6.2 Future development

The researchers developed two immersive prototypes: one in virtual reality (VR) stationary controller-based and one in mixed reality (MR) hand-tracking based spatial scanning, within a herbarium educational museum scenario, aimed at supporting active learning while investigating the impact of these emerging user interaction modalities on user experience. By following a human-centered design (HCD) approach throughout the development process, the solutions can continuously be iterated and refined for future work. Future improvements within development would benefit from involving a broader and more diverse user base, particularly by including a larger sample of museum visitors, to ensure that the prototypes more effectively align with institutional goals and visitor expectations. Additionally, expanding the participant pool would also strengthen the generalizability of the findings concerning user interaction preferences and learning outcomes. Although memory retention was considered in this study, its implications for long-term memory remain unclear, as assessments were conducted shortly after the experience. Future studies could therefore explore the sustained impact of these interaction modalities on long-term memory retention. Additionally, further refinement of both the VR and MR prototypes could focus on improving the onboarding process, especially in relation to controller-based interactions, in order to reduce cognitive load and enhance task clarity. Finally, further exploring adaptive interfaces and multimodal feedback systems may allow for more personalized and context-sensitive immersive educational experiences.

Appendix A

Link to video demos of the herbarium immersive VR & MR experiences prototypes

VR Prototype DEMO Preview

MR Prototype DEMO Preview

Appendix B

Interview guide for user testing

Interview guide for user testing of the virtual and mixed reality prototypes

Pre-user testing: 5-10 minutes

Welcoming the participants, and signing consent forms

The user testing is planned to last approximately 30-60 minutes to complete. The user testing will firstly start by welcoming the participants and presenting them with a consent form to sign, allowing each participant to have:

- an overview of what is being tested
- its purpose
- an understanding of how the confidentiality of the data collected during the test will be handled

To secure participant's personal data, preventing any unauthorized access and therefore making any type of personal data anonymous, each participant will be referred to as "Participant 1, 2, 3 etc…"

Pre-test interview

1. Have you visited a natural museum before?

2. How familiar are you with digital and/or interactive tools?

3. Do you have any previous experiences with Virtual or Mixed Reality technologies?

4. When learning something new, what helps you remember it best? Do you prefer exploring topics in depth, or rather get simpler and straightforward explanations?

5. What do you think of newer methods of exhibits interaction in museums nowadays? Does it make one's experience better or would you simply prefer to read from a label or see a video for example?

6. When visiting museums, what would make a learning experience more engaging and memorable for you?

Introducing VR/MR controls

Before each test of both prototypes, participants will get a short introduction to the controls in both the VR and MR prototypes in order to understand how to orient themselves in the environments. Note: This only applied for iteration one. In iteration two, a tutorial was implemented in the prototypes explaining the functionality of the controls.

User testing: 20-25 minutes

Participants will experience the virtual and mixed reality prototypes (different groups for each prototype → first iteration includes 2 tests, same applies for iteration 2) while performing given tasks. As participants are experiencing the prototypes, group members will be observing while the apps are being streamed to a computer. No recordings of both video or voice of the participants will be taken nor the screen will be recorded.

During the observations, the 'think aloud method' will be utilized, allowing the group members to have a more clear understanding of the user's thought process through the tasks.

Further, notes will be taken digitally using an observation record form as a foundation to analyse what participants are doing, or not doing during the test.

Note: Both prototype experiences are based on the same concept in terms of content and tasks.

User tasks

1. Explore the reception area and find the way to the herbarium lab
2. Equip the required outfit before entering the herbarium lab
3. Explore the pressing room and learn about the process of preparing a plant for research
4. Explore the main laboratory and learn about the process of taking a DNA test and archiving a prepared plant
5. Find and explore the temperature room and fix the sudden decrease of temperature of the herbarium lab to finish the experience

Post-user testing: Likert-Scale Questionnaire on SurveyXact, SUS (System usability scale) and a post-test interview 15-20 minutes

Questionnaire (Virtual Reality Experience - Stationary + Controllers)

General Info

1. Age?
2. Gender?
3. Field of occupation?
    a. Student
    b. Educator
    c. Other (Specify)
4. Have you used VR/MR before?
    a. Virtual Reality (VR)
    b. Mixed Reality (MR)
    c. Never used
5. Choose what applies to you:
    a. I had no knowledge on the topics/procedures before
    b. I had some knowledge on the topics/procedures before
    c. I had an average knowledge on the topics/procedures before
    d. I had a lot knowledge on the topics/procedures before
    e. I had quite a lot of knowledge on the topics/procedures before

6. I felt I learned about the topics:
    a. Herbarium (What is an herbarium and its purpose)
    b. Contamination measurements and safety
    c. Conservation (Pressing and preparing a plant)
    d. DNA test procedure
    e. Storage importance
    f. Temperature role and its role in preservation

User experience & Engagement (Strongly Agree - Strongly Disagree)

7. The experience was engaging.
8. The experience was enjoyable.
9. I felt guided throughout the experience.
10. The pacing of the experience kept me focused.
11. I felt frustrated while using the application.
12. Using the controllers to interact with the virtual environment felt intuitive.

13. Staying in a stationary (seated) position felt comfortable throughout the experience.
14. Navigating the environment using teleportation was easy to understand.
15. The narrator's instructions and visual elements (info boxes, audio etc.) were helpful and not distracting.
16. I was able to complete the tasks without confusion or difficulty.
17. The design of the environment and interactions felt consistent and well thought out.

Presence (Not at all - Completely) / Perception (Very unclear - Very clear)

18. I felt like I was really inside the herbarium environment.
19. I felt more focused and present while staying in a stationary position (seated).
20. I quickly adapted myself to the environment.
21. It felt natural to navigate around the environment while staying in a stationary position (seated).
22. I felt in control of my actions in the virtual environment.
23. The interactions with the virtual world felt natural and intuitive.
24. The environment felt realistic and believable.
25. The environment responded naturally to my actions.
26. Seeing a visualization of my hands while using the controllers made me feel more embodied and involved with the experience.
27. Using the controllers to examine and interact with objects felt responsive and natural.
28. I was so involved in the tasks that I lost track of time.
29. The sound made me feel more involved with experience.
30. I experienced motion sickness or discomfort during the experience.
    a. In the beginning
    b. During
    c. At the end
31. At the end of the experience, I felt I had control on how to navigate and interact with the environment.

32. The different stations of the environment (e.g. pressing a plant, DNA, contamination) were easy to identify.
33. I quickly understood what each station was for.
34. The layout of the virtual herbarium was easy to understand.
35. The information presented on the info screens was clear and easy to understand.
36. The amount of text and information felt overwhelming throughout the experience.

Memory retention (Strongly Agree - Strongly Disagree)

37. The VR experience encouraged me to actively engage with the learning material.
38. I felt involved in the learning process rather than just observing.
39. Being in a stationary (seated) position made it easier to focus on the learning tasks.
40. The controller-based interactions made the learning tasks feel structured and easy to follow.
41. Interacting with the environment helped me understand the herbarium topics.
42. The tasks and interactions made it easier to remember what I learned.
43. I feel confident I could explain at least one of the procedures I performed during the experience.
44. I feel I could replicate these procedures in a real world herbarium after experiencing it in a virtual world.
45. I am likely to remember what I learned in this experience a few days from now.
46. I believe I retained more information through this experience than I would have by reading or watching a video.
47. Being in a stationary position did not negatively impact my ability to learn or retain information.

Questionnaire (Mixed Reality Experience - Spatial Scanning + Hand Tracking)

General Info

48. Age?
49. Gender
50. Field of occupation?
    a. Student
    b. Educator
    c. Other (Specify)
51. Have you used VR/MR before?
    a. Virtual Reality (VR)
    b. Mixed Reality (MR)
    c. Never used
52. Choose what applies to you:
    a. I had no knowledge on the topics/procedures before
    b. I had some knowledge on the topics/procedures before
    c. I had an average knowledge on the topics/procedures before
    d. I had a lot knowledge on the topics/procedures before

53. I felt I learned about the topics:

    a. Herbarium (What is an herbarium and its purpose)
    b. Contamination measurements and safety
    c. Conservation (Pressing and preparing a plant)
    d. DNA test procedure
    e. Storage importance
    f. Temperature role and its role in preservation

User experience & Engagement (Strongly Agree - Strongly Disagree)

54. The experience was engaging.
55. The experience was enjoyable.
56. The pacing of the experience kept me focused.
57. I felt frustrated while using the application.
58. It felt intuitive to use my hands to interact with the environment.
59. I felt comfortable and natural to physically move around during the experience.
60. The narrator's instructions and visual elements (info boxes, audio etc.) were helpful and not distracting.
61. I was able to complete the tasks without feeling confused or frustrated.
62. The design of the environment and interactions felt consistent and well thought out.

Presence (Not at all - Completely) / Perception (Very unclear - Very clear)

63. I felt like I was really inside the herbarium.
64. Seeing real-world objects around me did not distract me.
65. Physically moving through the space did not disrupt the experience.
66. I quickly adapted to the environment.
67. I had control over my actions in the environment.
68. I could interact and examine objects in the experience.
69. The virtual objects placed onto the real world felt believable and realistic.
70. The environment was responsive according to my actions.
71. Using my hands made me feel more physically present and embodied in the environment.
72. Using my hands as a way of interaction distracted me from performing the different tasks.
73. Interacting with objects using my hands felt responsive and satisfying.
74. I was so involved in the tasks that I lost track of time.
75. I experienced motion sickness or discomfort during the experience.
    a. In the beginning
    b. During
    c. At the end
76. The sound made me feel more involved with experience.

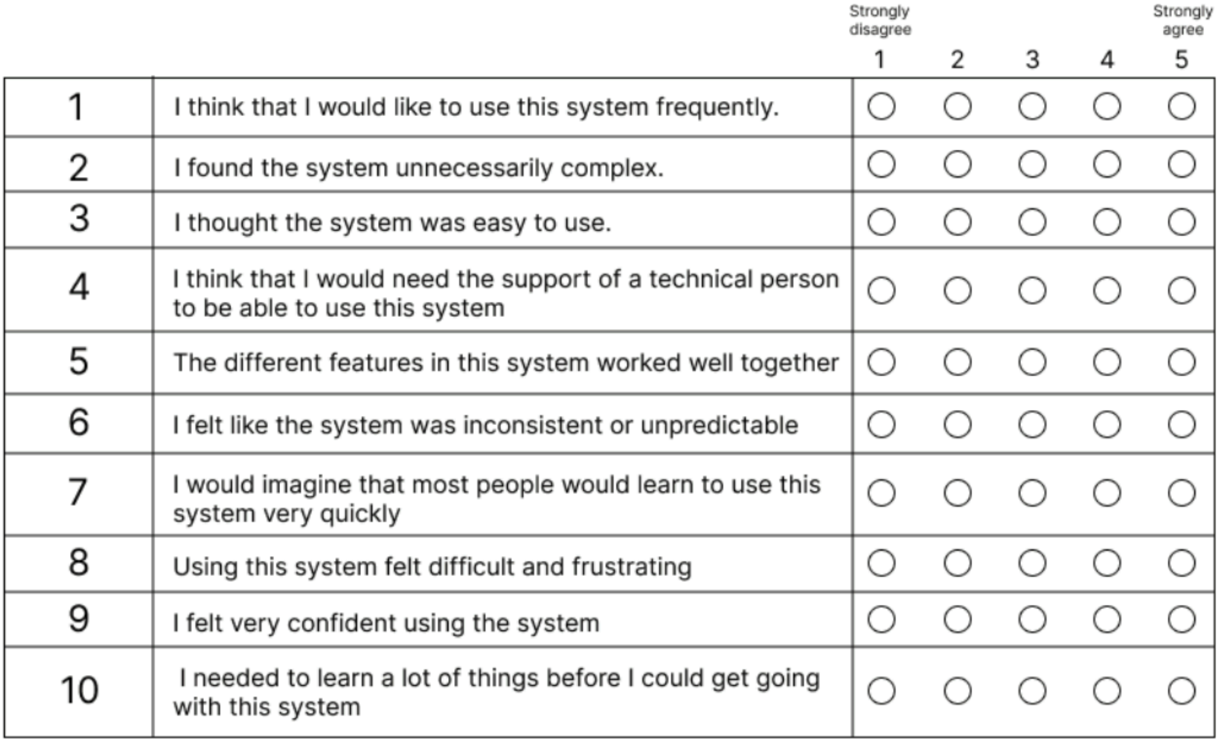
77. At the end of the experience, I felt I had control on how to navigate and interact with the environment.

78. The different stations of the environment (e.g. pressing a plant, DNA, contamination) were easy to identify.
79. I quickly understood what each station was for.
80. Interacting with the info screens using my hands felt natural.
81. The layout of the virtual herbarium was easy to understand.
82. The information presented on the info screens was clear and easy to understand.
83. The amount of text and information felt overwhelming throughout the experience.

Memory retention (Strongly Agree - Strongly Disagree)

84. The mixed reality experience encouraged me to actively engage with the content.
85. I felt involved in the learning process rather than just observing.
86. Interacting with the environment helped me understand the herbarium-related topics better.
87. The tasks and interactions made it easier to remember what I learned.
88. I feel confident I could explain some of the procedures I learned during the experience.
89. I feel I could replicate these procedures in a real world herbarium after experiencing it in a virtual world.
90. I believe I retained more information through this experience than I would have by reading or watching a video.
91. I am likely to remember what I learned in this experience a few days from now.
92. Being able to physically move around positively had an impact on my ability to learn or retain information.
93. Being able to use my hands to interact in the environment positively had an impact on my ability to learn and retain information.

System Usability Scale (SUS)



		Strongly disagree 1	2	3	4	Strongly agree 5
1	I think that I would like to use this system frequently.	○	○	○	○	○
2	I found the system unnecessarily complex.	○	○	○	○	○
3	I thought the system was easy to use.	○	○	○	○	○
4	I think that I would need the support of a technical person to be able to use this system	○	○	○	○	○
5	The different features in this system worked well together	○	○	○	○	○
6	I felt like the system was inconsistent or unpredictable	○	○	○	○	○
7	I would imagine that most people would learn to use this system very quickly	○	○	○	○	○
8	Using this system felt difficult and frustrating	○	○	○	○	○
9	I felt very confident using the system	○	○	○	○	○
10	I needed to learn a lot of things before I could get going with this system	○	○	○	○	○

Post-test interview (Virtual Reality Experience - Stationary + Controllers)

1. How was your experience using the prototype? Elaborate

2. How did you feel about using the controllers as a way of interaction in the experience? Did they feel intuitive or limiting in any way?

3. How did you feel about remaining stationary throughout the experience? Did the teleportation method of navigation feel comfortable or restrictive?

4. Did the tasks you performed engage you in the learning process? Were you able to feel involved and active in your learning, or did you feel more passive in your experience?

5. Would you say that learning this way is a way to make the content memorable for you? Any other way of interaction that you would prefer?

6. In your opinion, do you think Virtual Reality is an effective tool for enhancing educational content in museums? How so?

Memory Retention Test:

7. Could you walk me through the steps or processes you remember before entering the herbarium lab in the VR experience? What stood out to you?

8. Can you recall one of the tasks you performed (such as pressing a plant or conducting a DNA test)? What details do you remember about that task?

9. Do you remember why certain procedures, like using protective gear, drying a pressed plant or regulating the temperature, were important in the context of the tasks? Can you explain why they matter?

10. Do you remember the name of the plant that you worked with in the experience?

11. Do you remember where you had to archive the plant and why it's important to archive the plants in a specific structure?

12. Do you remember what information you got out of the DNA test?

13. What was the minimum and the maximum optimal temperature to store the plants?

14. Were there any facts or pieces of information that stood out to you during the experience? If yes, what were they?

15. Did physically performing the tasks yourself (rather than simply observing or reading about them) help you remember the information more effectively? Please explain why or why not.

Improvement and Feedback:

16. Is there anything that was lacking in the experience that you would change or improve?

17. Do you have any other thoughts, comments, or suggestions on how this VR experience could be improved or adjusted for better educational value?

Post-test interview (Mixed Reality Experience - Spatial Scanning + Hand Tracking)

1. How was your experience using the prototype? Was there anything particularly enjoyable or frustrating? Elaborate

2. How did you feel about using hand tracking as a way of interaction in the experience? Did it feel intuitive, or were there limitations or difficulties you encountered?

3. How did it feel to physically move around the space to navigate the environment? Did it enhance your experience or create any challenges? Elaborate

4. Did the tasks you performed engage you in the learning process? Were you able to feel involved and active in your learning, or did you feel more passive in your experience?

5. Would you say that learning by interacting using hand tracking and being able to physically move around is a way to make the content more memorable for you? Any other way of interaction that you would prefer?

6. In your opinion, do you think mixed reality technologies, like spatial scanning and hand tracking, can have a positive impact on museum education and improve the way you learn? Why or why not?

Memory Retention Test

7. Could you walk me through the steps or processes you remember before entering the herbarium lab in the VR experience? What stood out to you?

8. Can you recall one of the tasks you performed (such as pressing a plant or conducting a DNA test)? What details do you remember about that task?

9. Do you remember why certain procedures, like using protective gear, drying a pressed plant or regulating the temperature, were important in the context of the tasks? Can you explain why they matter?

10. Do you remember the name of the plant that you worked with in the experience?

11. Do you remember where you had to archive the plant and why it’s important to archive the plants in a specific structure?

12. Do you remember what information you got out of the DNA test?

13. What was the minimum and the maximum optimal temperature to store the plants?

14. Were there any facts or pieces of information that stood out to you during the experience? If yes, what were they?

15. Did physically performing the tasks yourself (rather than simply observing or reading about them) help you remember the information more effectively? Please explain why or why not.

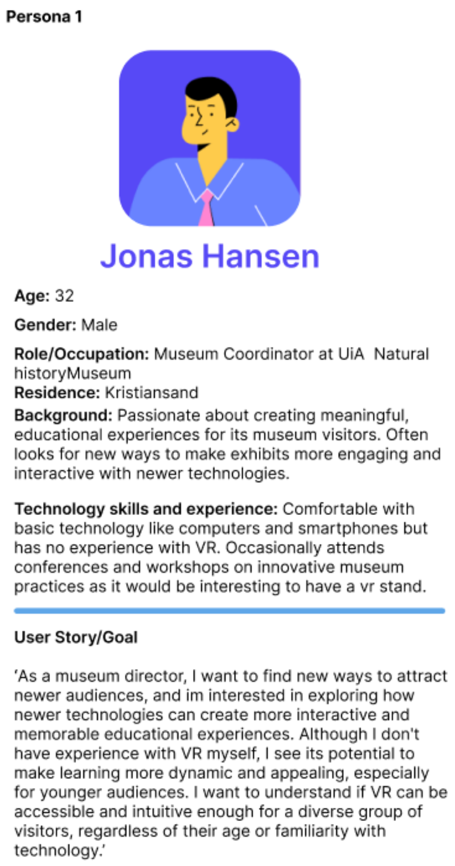
Improvement and Feedback:

16. Is there anything that was lacking in the experience that you would change or improve?

17. Do you have any other comments or ideas you would like to add?

Appendix C

Personas



Persona 1

Jonas Hansen

Age: 32

Gender: Male

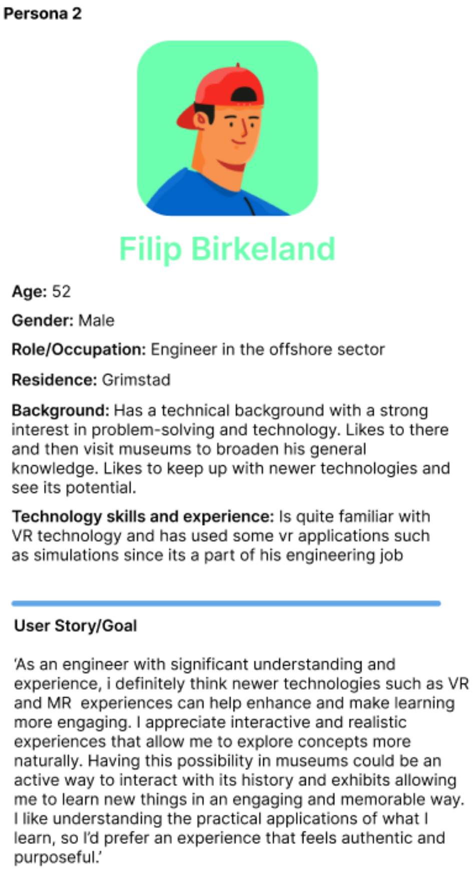
Role/Occupation: Museum Coordinator at UiA Natural historyMuseum
Residence: Kristiansand

Background: Passionate about creating meaningful, educational experiences for its museum visitors. Often looks for new ways to make exhibits more engaging and interactive with newer technologies.

Technology skills and experience: Comfortable with basic technology like computers and smartphones but has no experience with VR. Occasionally attends conferences and workshops on innovative museum practices as it would be interesting to have a vr stand.

User Story/Goal

'As a museum director, I want to find new ways to attract newer audiences, and im interested in exploring how newer technologies can create more interactive and memorable educational experiences. Although I don't have experience with VR myself, I see its potential to make learning more dynamic and appealing, especially for younger audiences. I want to understand if VR can be accessible and intuitive enough for a diverse group of visitors, regardless of their age or familiarity with technology.'



Persona 2

Filip Birkeland

Age: 52

Gender: Male

Role/Occupation: Engineer in the offshore sector

Residence: Grimstad

Background: Has a technical background with a strong interest in problem-solving and technology. Likes to there and then visit museums to broaden his general knowledge. Likes to keep up with newer technologies and see its potential.

Technology skills and experience: Is quite familiar with VR technology and has used some vr applications such as simulations since its a part of his engineering job

User Story/Goal

'As an engineer with significant understanding and experience, i definitely think newer technologies such as VR and MR experiences can help enhance and make learning more engaging. I appreciate interactive and realistic experiences that allow me to explore concepts more naturally. Having this possibility in museums could be an active way to interact with its history and exhibits allowing me to learn new things in an engaging and memorable way. I like understanding the practical applications of what I learn, so I'd prefer an experience that feels authentic and purposeful.'

Persona 3

Anna Jessheim

Age: 25

Gender: Female

Role/Occupation: Biology Student at UiA

Residence: Kristiansand

Background: Is an active person and likes to frequently visit museums in her free time for educational purposes. Finds traditional museum exhibits less interactive and struggles to stay engaged with just observing and reading.

Technology skills and experience: Familiar with digital tools but has very limited knowledge in mixed or virtual reality. Has only seen it in videos and has been interested in trying it out ever since and its diverse ways of interaction.

User Story/Goal

'As a biology student with a strong interest in plant science and exploring new methods of learning, I would like to experience a virtual herbarium to learn in a more interactive and engaging way. Since I'm an active person, I feel more engaged when I can physically move around and interact with my own hands, rather than just staying still and clicking on controller buttons to interact. I liked to have things explained to me in a structured and concise way. I believe that this kind of experience could help me better understand botanical concepts and make the learning process more memorable and meaningful.'

Persona 4

Frida Andersen

Age: 72

Gender: Female

Role/Occupation: Retired nurse

Residence: Søgne

Background: Enjoys visiting museums, botanical gardens, and cultural institutions during her free time. Has valued learning and enjoys expanding her general knowledge on diverse topics.

Technology skills and experience: Comfortable with using her phone for basic tasks, however still adapting to newer technologies. Has no prior experience with VR but is curious about modern technology. Prefers practical, hands-on experiences but is cautious about complex, fast-paced technology

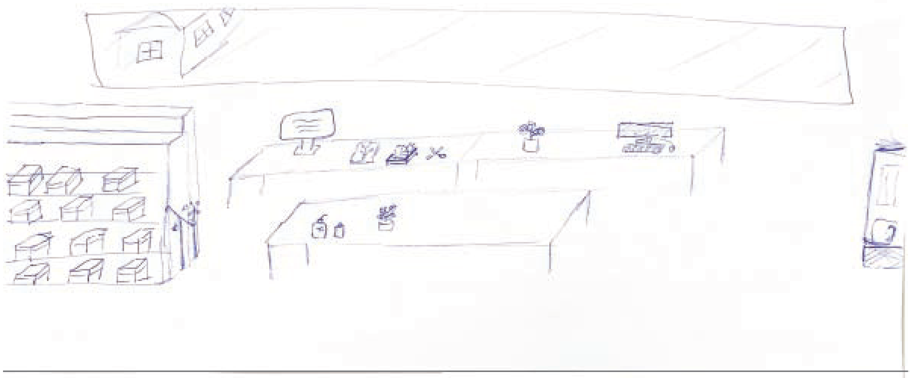
User Story/Goal

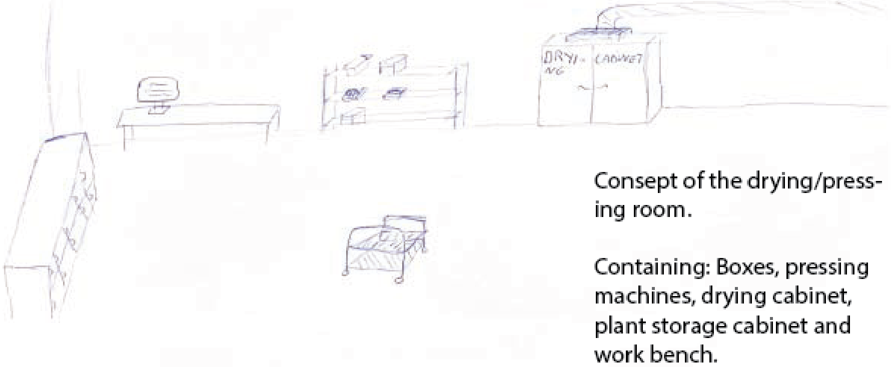
'As a retired person who has always enjoyed visiting museums and learn new things, I am curious about how technologies like VR or MR can make exhibits more engaging and memorable. Although I don't have much experience with VR or MR, I would like to explore it if it's easy to use and a fun experience. I appreciate learning at my own pace and like experiences that feel realistic and meaningful rather than purely for entertainment.'

Appendix D

Storyboards

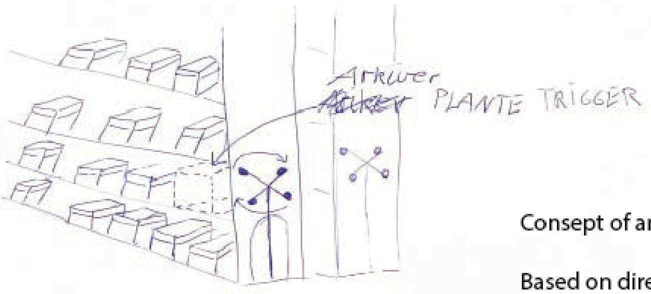
Visualisation of the lab with window showing the outside area.
Based on refferance pictures from guided tour at the museum.





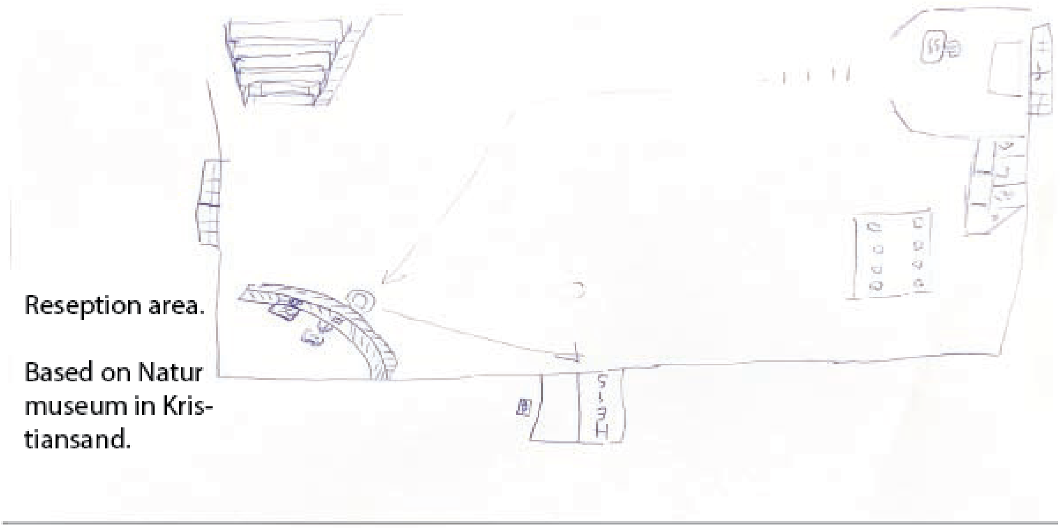
Consept of the drying/pressing room.

Containing: Boxes, pressing machines, drying cabinet, plant storage cabinet and work bench.



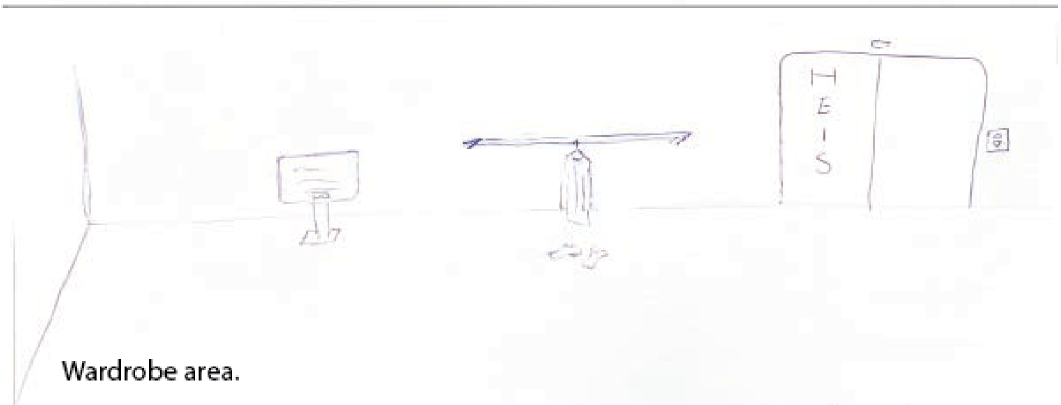
Consept of arkive storage.

Based on direct observation made during trip to Natur museum KRistiansand.

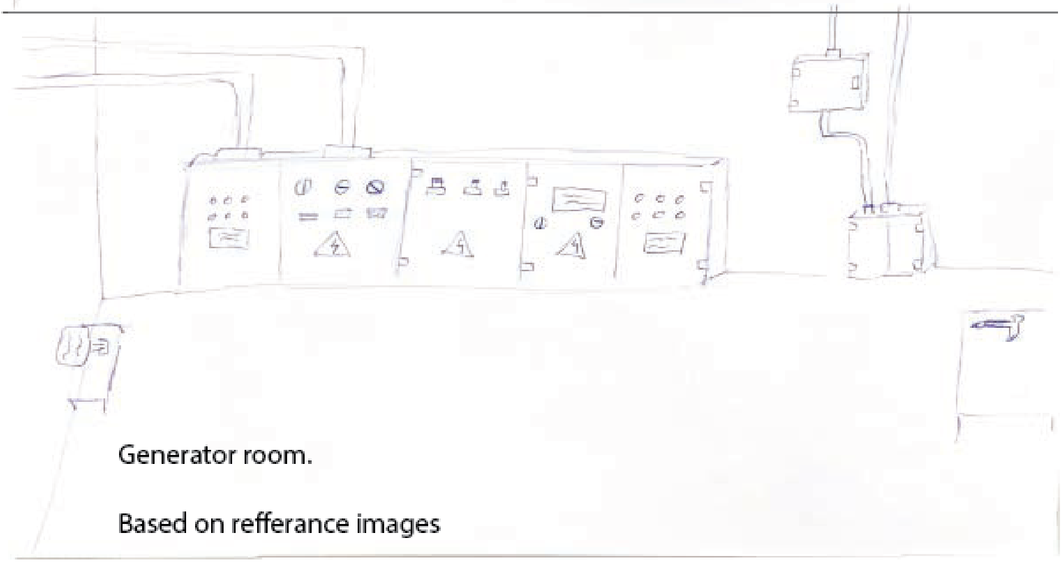


Reseption area.

Based on Natur museum in Kristiansand.



Wardrobe area.

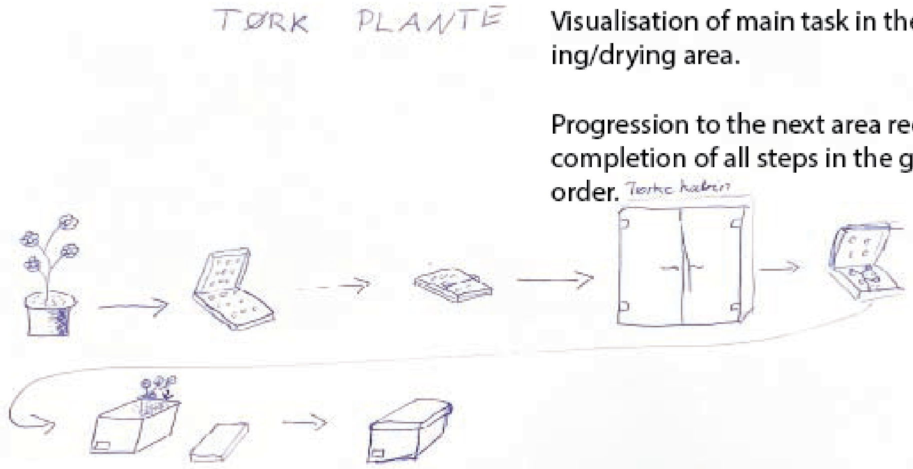


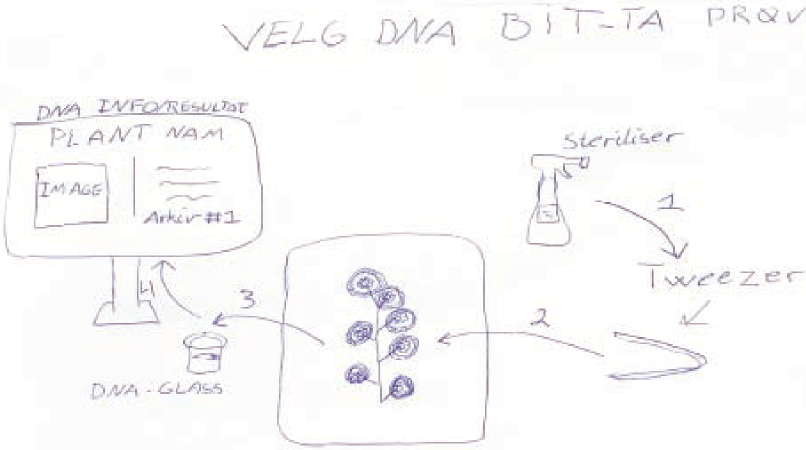
Generator room.

Based on refferance images

Visualisation of main task in the pressing/drying area.

Progression to the next area requires completion of all steps in the given order.


TØRK PLANTE
Tørke kabin

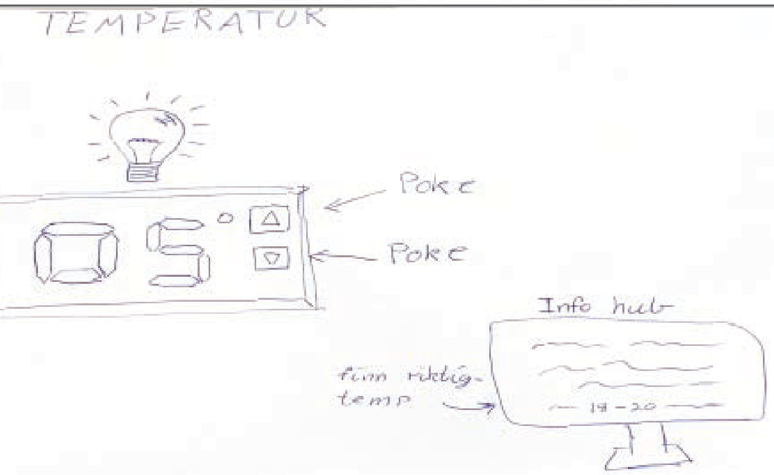

VELG DNA BIT-TA PRØVE
DNA INFO/RESULTAT
PLANT NAM
IMAGE
Arkiv #1
4
Steriliser
1
Tweezer
2
3
DNA - GLASS

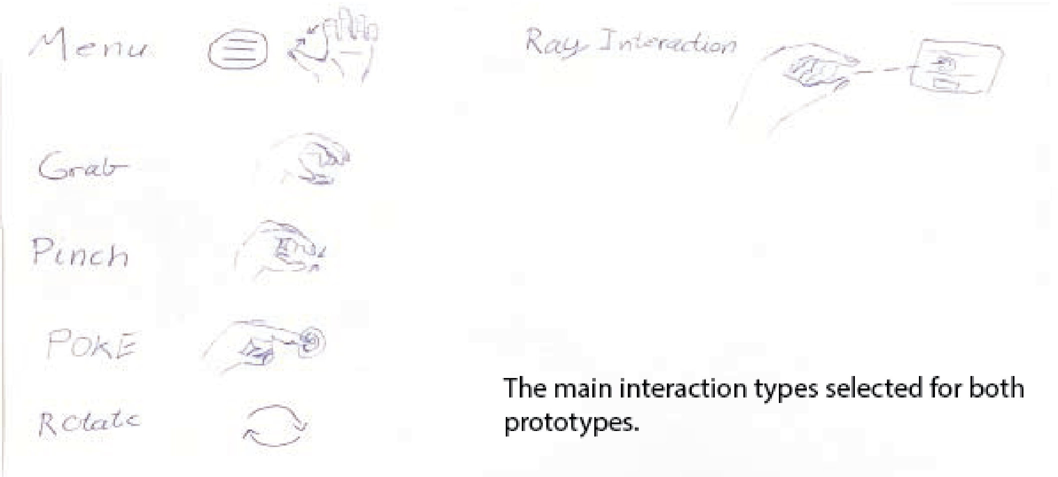
Task Visualization: Steps that must be completed in sequence:

1:Sterilize the tweezers.
2:Pick a suitable DNA piece.
3:Place piece inDNA container.
4:Retrieve plant info.

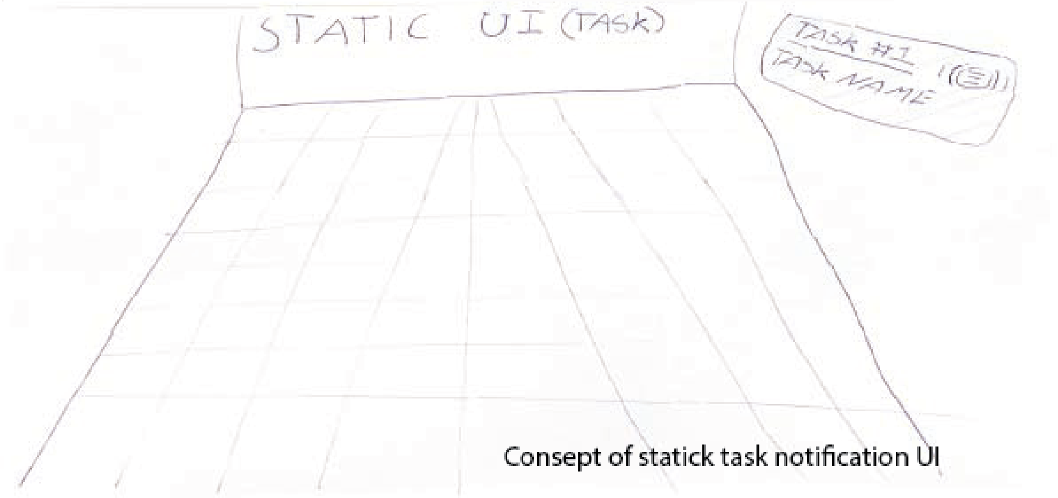
Task Visualization: Setting the right temperature.

Find correct temperature in info screen/hub, then sett the temperature.


TEMPERATUR
05°
Poke
Poke
Info hub
finn riktig temp
19 - 20

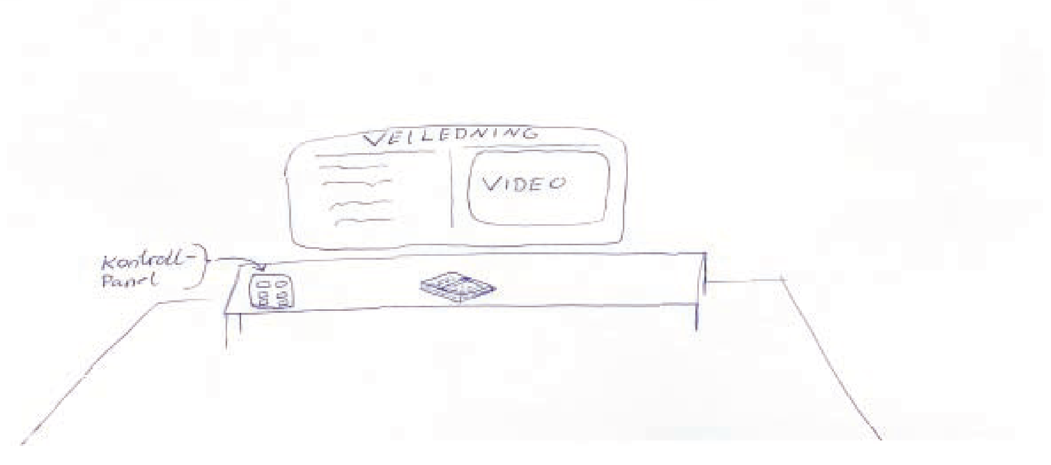

Menu
Ray Interaction
Grab
Pinch
POKE
Rotate

The main interaction types selected for both prototypes.

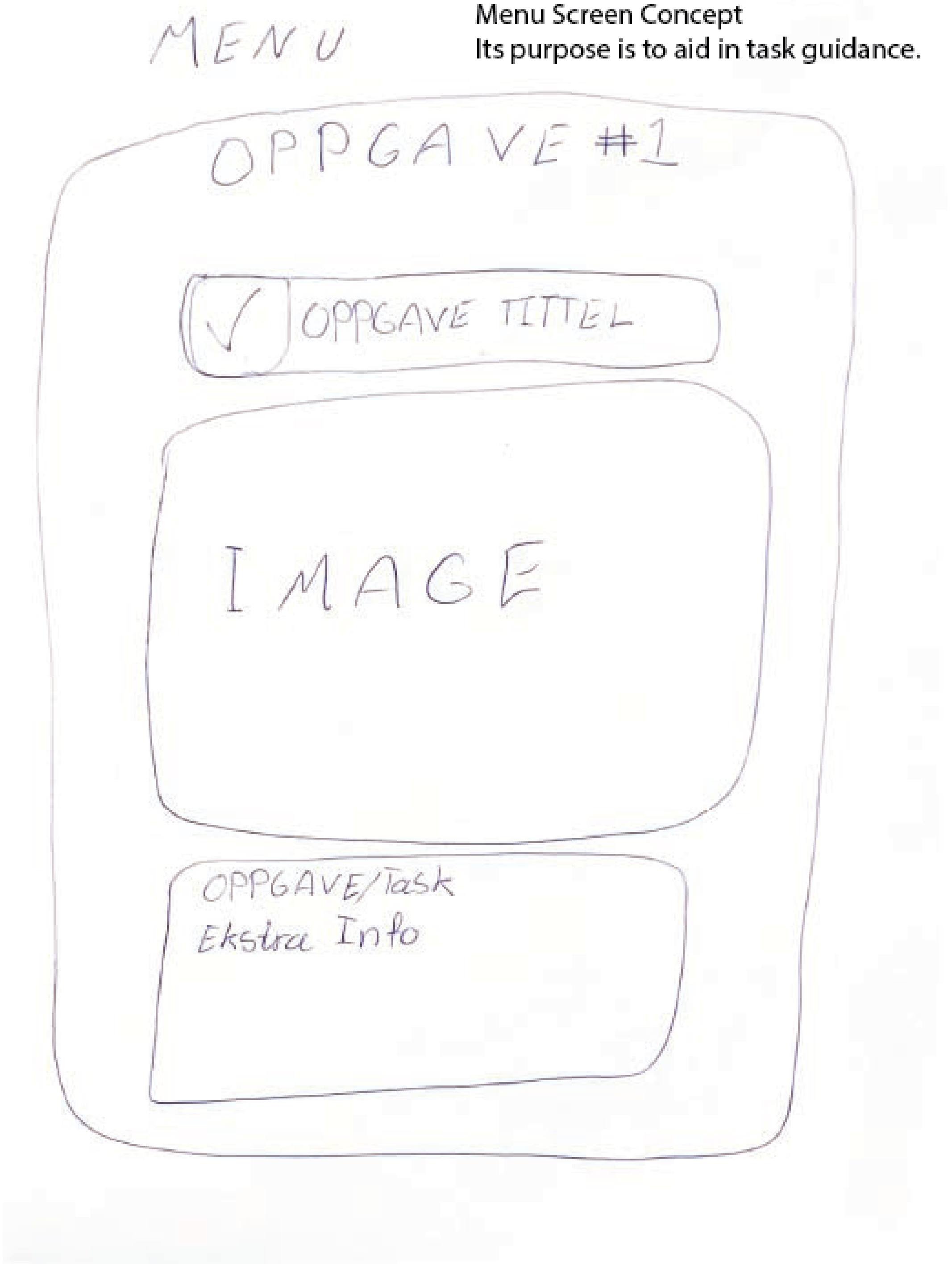

STATIC UI (TASK)
TASK #1
TASK NAME

Consept of statick task notification UI

Tutorial area consept.

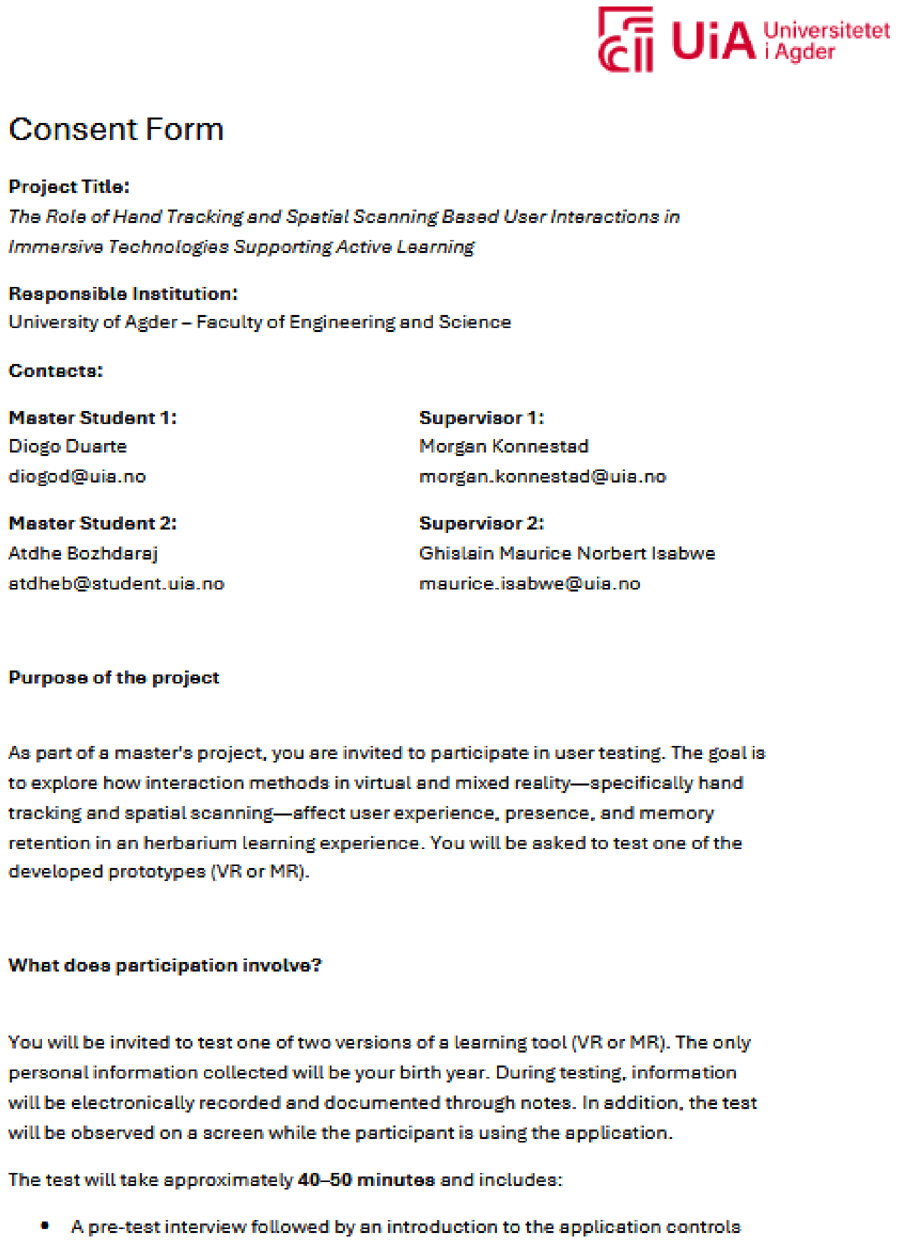

VEILEDNING
VIDEO
Kontroll-Panel

Menu Screen Concept
Its purpose is to aid in task guidance.


MENU
OPPGAVE #1
✓ OPPGAVE TITTEL
IMAGE
OPPGAVE/Task
Ekstra Info

Appendix E

Consent form



Consent Form

Project Title:
The Role of Hand Tracking and Spatial Scanning Based User Interactions in Immersive Technologies Supporting Active Learning

Responsible Institution:
University of Agder – Faculty of Engineering and Science

Contacts:

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Ghislain Maurice Norbert Isabwe
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Purpose of the project

As part of a master's project, you are invited to participate in user testing. The goal is to explore how interaction methods in virtual and mixed reality—specifically hand tracking and spatial scanning—affect user experience, presence, and memory retention in an herbarium learning experience. You will be asked to test one of the developed prototypes (VR or MR).

What does participation involve?

You will be invited to test one of two versions of a learning tool (VR or MR). The only personal information collected will be your birth year. During testing, information will be electronically recorded and documented through notes. In addition, the test will be observed on a screen while the participant is using the application.

The test will take approximately **40–50 minutes** and includes:

- A pre-test interview followed by an introduction to the application controls

- A VR or an MR experience in a simulated museum setting displayed on a screen for observers
- Evaluation of the system using the System Usability Scale (SUS)
- A post-test questionnaire and a short interview after the session

Privacy and Data Processing

The project collects limited information in order to analyze user experiences in a systematic way. The following personal information is recorded: year of birth. Only the students Diogo Duarte and Atdhe Bozhdaraj, along with other internal collaborators, will have access to the collected data/information.The data is stored on a secure platform and is used solely for this project. It will not be possible to identify you in analyses, reports, or publications. When the project concludes, all collected data will be permanently deleted.

Voluntary Participation and Right to Withdraw

Participation is completely voluntary, and you may withdraw from the testing at any time. You may ask questions at any time during the test. All information, including quotes, will be **anonymized** and treated **confidentially**. Participants cannot be identified, and ages will be published in 5-year intervals. After the project ends, all collected data will be destroyed.

Project end date: **30.05.2025**

Consent
By signing below, I confirm that:

- I have read and understood the information about the project
- I voluntarily consent to participate in the study
- I consent to excerpts from the user testing being included in publications and quotations as long as they are anonymized.
- I agree that my information will be processed until the project is concluded

Participant's signature: ______________________________

Date: ______________________________

Appendix F

PACT analysis

People

Each individual is different when it comes to social, physical and psychological aspects. While it is important to consider principal users who are going to use the product, it is also fundamental that the solution considers other categories of stakeholders, including individuals that are affected and concerned by the system. The primary users are intended to be museum visitors, which can be any type of person with any type of technical background and expertise. Talks with the museum expressed that a wide variety of the visitors involve high-school and university students. Some may prefer or require a stationary experience, while others might enjoy room-scale movement. So the solutions should focus on a stationary(seated or standing) and room-scale experience where the users can freely and physically move around an environment. Some may have challenges reading content as well as become overwhelmed in a virtual reality environment, therefore the information should be accompanied by a narrator voice that facilitates this process. For others who prefer, full text information should be available.

Virtual and mixed Reality technologies are still significantly novel. Not everyone is quite familiar with it or has experienced it at all, especially elderly audiences. However, it has steadily become more popular among educational and other settings. The solutions, whether being used with hand tracking or controllers, should be intuitive, natural and enjoyable, avoiding challenges for users who are both unfamiliar and familiar with the technology. Clear user guidance should be provided throughout the experience to help users understand how to interact and navigate in the environments. Additionally, an introductory tutorial should be given in both prototype approaches, allowing users to understand the controls and inputs prior to the experience rather than spending time during the experience worrying about these.

Activities

The proposed solutions revolve around exploring a virtual herbarium facilitated by an HMD. Two approaches are taken into consideration, involving the same use case scenario. Therefore, only the interaction modalities should differ and approaches, meaning one in full VR while the other in MR with pass-through. Through these experiences, users will learn about botanical research and complete diverse tasks performed in the herbarium, where they will be guided throughout the process. The proposed tasks must be completed in a structured order so that users understand the foundational process, as these tasks build upon each other.

In the stationary solution, users will primarily interact with hand controllers using analog buttons to turn and action buttons to interact, while in the room-scale, users rely on hand tracking. Interaction will be performed by grabbing, pinching and poking. With or without the help of a tutorial, it should be easy for users to understand and apply these methods

Context

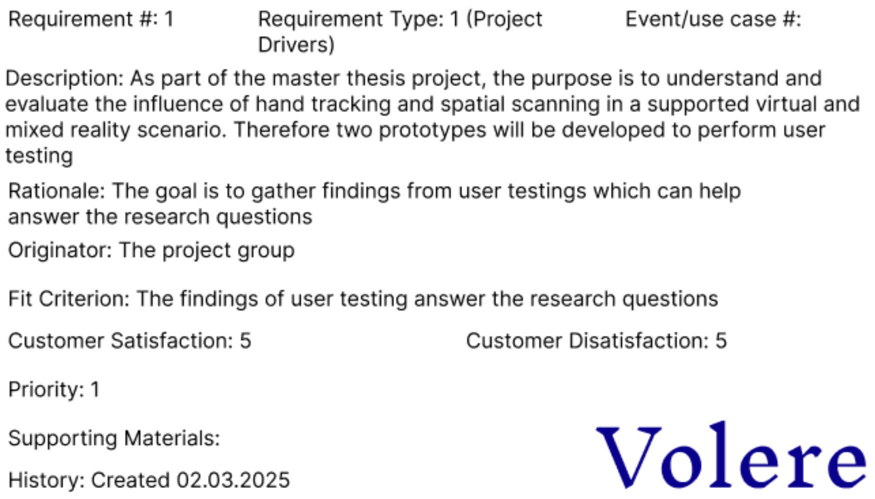
The proposed solutions are intended for use in a natural museum environment aimed at its visitors to teach about the herbarium, however the approaches utilized are intended to be adopted in any dedicated educational environment and use case. For instance in education, engineering, healthcare etc. The solutions are in standalone applications in the headset, meaning no computer is required to be connected in order to run the solutions. Ideally, it should be indoors where there is enough room and lighting. The stationary prototype has the goal of being utilized by either standing still or sitting on a chair and interacting with the controllers, while the spatial scanning prototype requires a dedicated area where the user can freely move around, unpresent of other people, and interact with the herbarium application while using hand tracking. The prototypes portray the same content, however in two different concepts and ways of interacting.

Technology

The solutions are designed specifically for the Meta Quest 3 HMD. In comparison to the previous versions, Quest 1, Quest 2 and Quest pro, Quest 3 has significant hardware improvements in display refresh rate, resolution, tracking and features such as improved pass-through and spatial mapping, which play a significant role in allowing the user to have a better experience.

Appendix G

Volere Shells requirements



Requirement #: 1
Requirement Type: 1 (Project Drivers)
Event/use case #:

Description: As part of the master thesis project, the purpose is to understand and evaluate the influence of hand tracking and spatial scanning in a supported virtual and mixed reality scenario. Therefore two prototypes will be developed to perform user testing

Rationale: The goal is to gather findings from user testings which can help answer the research questions

Originator: The project group

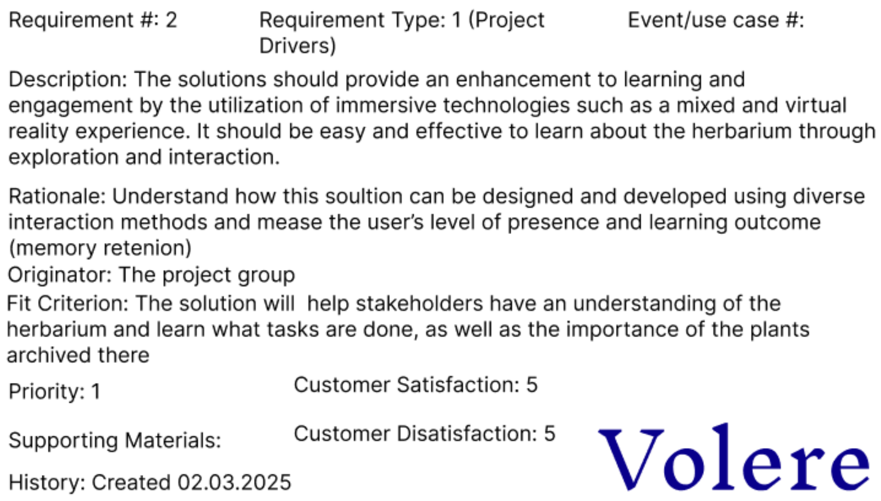
Fit Criterion: The findings of user testing answer the research questions

Customer Satisfaction: 5
Customer Disatisfaction: 5

Priority: 1

Supporting Materials:

History: Created 02.03.2025



Requirement #: 2
Requirement Type: 1 (Project Drivers)
Event/use case #:

Description: The solutions should provide an enhancement to learning and engagement by the utilization of immersive technologies such as a mixed and virtual reality experience. It should be easy and effective to learn about the herbarium through exploration and interaction.

Rationale: Understand how this soultion can be designed and developed using diverse interaction methods and mease the user’s level of presence and learning outcome (memory retenion)

Originator: The project group

Fit Criterion: The solution will help stakeholders have an understanding of the herbarium and learn what tasks are done, as well as the importance of the plants archived there

Priority: 1
Customer Satisfaction: 5

Supporting Materials:
Customer Disatisfaction: 5

History: Created 02.03.2025

Requirement #: 3 Requirement Type: 3 (Project Constraints) Event/use case #:

Description: The solution is targeted for the Meta Quest 3

Rationale: Being one of the most recent SDKs launched with high spatial scanning and hack tracking capabilities, also supporting stationary and controller-based version.

Originator: The project group

Fit Criterion: The two developed solutions include two functional prototypes that can be ran directly from the Meta Quest 3 - Mixed Reality Prototype (with passthrough) and a stationary version.

Priority: 1 Customer Satisfaction: 2 Customer Disatisfaction: 3

Supporting Materials: VR development guidelines, Meta Quest 3 SDK docuimentation

History: Created 02.03.2025

Volere

Requirement #: 4 Requirement Type: 3 (Project Constraints) Event/use case #:

Description: The solutions are designed for museum visitors, including casual visitors, students, educators with varying levels of familiarity with VR technology.

Rationale: The solutions are aimed at museum visitors: students, educators etc. Overall the general population who has an interest in visiting natural museums.

Originator: The project group

Fit Criterion:

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 5

Supporting Materials: Museum visitors demographics

History: Created 02.03.2025

Volere

Requirement #: 5 Requirement Type: 9 (Functional Requirements) Event/use case #:

Description: The VR solution must allow users to interact with the environment by grabbing, poking, and ray interactions

Rationale: Gives the user control and makes the experiences feel immersed as hands are visualized while using controllers.

Originator: The project group

Fit Criterion: Users must be able to grab, poke and ray using controller inputs

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 2

Supporting Materials: Meta SDK documentation

History: Created 05.03.2025

Volere

Requirement #: 6 Requirement Type: 9 (Functional Requirements) Event/use case #:

Description: The MR solution must allow users to interact with the environment by grabbing, poking, pinching, and ray interactions

Rationale: Gives the user control and a more natural interaction feeling and makes the experiences feel immersed as the user uses their own hands to interact

Originator: The project group

Fit Criterion: Users must be able to grab and inspect objects with their hands, pinch UI using ray and buttons by poking

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 2

Supporting Materials: Meta SDK documentation

History: Created 05.03.2025

Volere

Requirement #: 7 Requirement Type: 9 (Functional Requirements) Event/use case #:

Description: The VR solution must provide a teleportation-based movement system for users to navigate the environment

Rationale: Can help minimize motion sickness and improve accessibility and usability for users who are physically incapable of walking.

Originator: The project group

Fit Criterion: Users must point to a location in the environment and teleport using the controller joysticks.

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 4

Supporting Materials: Meta SDK documentation, Unity Input System

History: Created 05.03.2025

Volere

Requirement #: 8 Requirement Type: 9 (Functional Requirements) Event/use case #:

Description: The MR solution must utilize spatial scanning features within the Meta Quest 3 to allow users to navigate within a scanned version of a physical space, enabling free movement in the environment.

Rationale: Can help minimize motion sickness, enhance sense of presence, however decrease the accessibility aspect where users unable to walk can not experience.

Originator: The project group

Fit Criterion: The solutions must detect and map the user’s area before starting the experience. Users must thereafter walk natural in the environment.

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 4

Supporting Materials: Meta SDK documentation, Spatial Scanning Technology in the Meta Quest 3

History: Created 05.03.2025

Volere

Requirement #: 9
Requirement Type: 9 (Functional Requirements)
Event/use case #:

Description: The solutions must include an adaptive guidance system that provides visual hints, instructions and a voice narrator to assist users in interacting with the environment.

Rationale: Since some users may be unfamiliar with VR interactions, on-screen prompts, tool tips, and voice guidance will ensure a smoother experience

Originator: The project group

Fit Criterion: Audio narratives and visual cues will help the user understand what to do.

Priority: 1
Customer Satisfaction: 5
Customer Disatisfaction: 3

Supporting Materials: Unity UI system, Meta Quest 3 audio integration

History: Created 22.04.2025

Volere

Requirement #: 10
Requirement Type: 9 (Functional Requirements)
Event/use case #:

Description: The solutions must include interactive info screen places throughout the environment, allowing users to read or listen to theoretical information about the herbarium and track task completion progress. Clear buttons should be available to interact with the info screens.

Rationale: The solutions are designed for educational purposes, users need access to important theoretical knowledge while also keeping track of their learning progress. The option to read and/or listen enhances accessibility and engagement.

Originator: The project group

Fit Criterion: Info screens must provide text-based and audio narration options. Must provide user tasks progression status.

Priority: 1
Customer Satisfaction: 5
Customer Disatisfaction: 4

Supporting Materials: Unity UI system, Meta Quest 3 audio integration

History: Created 05.03.2025

Volere

Requirement #: 11
Requirement Type: 10 (Non-Functional Requirements)
Event/use case #:

Description: The solutions should run smoothly on the Meta Quest 3 ensuring a comfortable and immersive experience while diminishing motion sickness

Rationale: High-performance VR/MR application reduce latency and motion sickness, ensuring users remain engaged without discomfort

Originator: The project group

Fit Criterion: The application must have no noticeable frame drops and interactions must have a low latency and feel responsive

Priority: 1
Customer Satisfaction: 5
Customer Disatisfaction: 5

Supporting Materials: Optimization techniques

History: Created 06.03.2025

Volere

Requirement #: 12
Requirement Type: 10 (Non-Functional Requirements)
Event/use case #:

Description: The solutions must be easy to learn how to use and easy to remember how to use.

Rationale: Users have varied levels of VR experience, so the interface, inputs must be intuitive and easy to understand

Originator: The project group

Fit Criterion: Onboarding should take no longer than 3 minutes for the users

Priority: 1
Customer Satisfaction: 5
Customer Disatisfaction: 5

Supporting Materials: User testing

History: Created 06.03.2025

Volere

Requirement #: 13
Requirement Type: 10 (Non-Functional Requirements)
Event/use case #:

Description: The solutions must as accurately as possible replicate the look and feel of a real herbarium environment, including the museum entrance and lab setting, to ensure an authentic and educational experience

Rationale: The solution must showcase the real look of an herbarium and teach about theoretical concepts of the tasks performed there, therefore the look and feel of the solutions should support that.

Originator: The project group

Fit Criterion: Realistic environment, consistent, lighting and high quality texturing to ensure an accurate representation of the environments

Priority: 1
Customer Satisfaction: 5
Customer Disatisfaction: 3

Supporting Materials: User testing

History: Created 06.03.2025

Volere

Requirement #: 14
Requirement Type: 9 (Functional Requirements)
Event/use case #:

Description: The solutions must include an in game introductory tutorial accessible to users before “starting” the experience, allowing users to become familiar with the controlls.

Rationale: Serves as an entry point, offering a clear, intuitive way to access a tutorial if chosen, enhancing usability and accessibility.

Originator: The project group

Fit Criterion: Main menu must include a tutorial option.

Priority: 1
Customer Satisfaction: 3
Customer Disatisfaction: 3

Supporting Materials: Unity UI System

History: Created 15.04.2025

Volere

Requirement #: 15 Requirement Type: 10 (Non-Functional Requirements) Event/use case #:

Description: There should be audio feedback when the user is performing certain interaction.

Rationale: Allows the user to have a higher level of presence and makes the interactions responsive to the users actions (e.g poking a button, elevator sound)

Originator: The project group

Fit Criterion: Sound feedback should be heard when performing interactions

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 4

Supporting Materials: Unity spatial audio

History: Created 07.03.2025

Volere

Requirement #: 16 Requirement Type: 10 (Non-Functional Requirements) Event/use case #:

Description: The tasks and activities performed in the solutions must be authentic and accurately reflect real-life scenarios that take place in an actual herbarium for the users to learn about.

Rationale: Ensuring the accuracy of tasks enhances the educational value of the experience

Originator: The project group

Fit Criterion: An observation was consulted with a herbarium researcher ensuring tasks are done based on reliable expert knowledge.

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 5

Supporting Materials: Observation notes at the herbarium.

History: Created 07.03.2025

Volere

Requirement #: 17 Requirement Type: 10 (Non-Functional Requirements) Event/use case #:

Description: The theoretical information in the info screen must be reliable, concise, easy to understand and fact-based.

Rationale: The information should be educational and connect with the herbarium tasks performed, as well as concise and easy to give users a shortened overview.

Originator: The project group

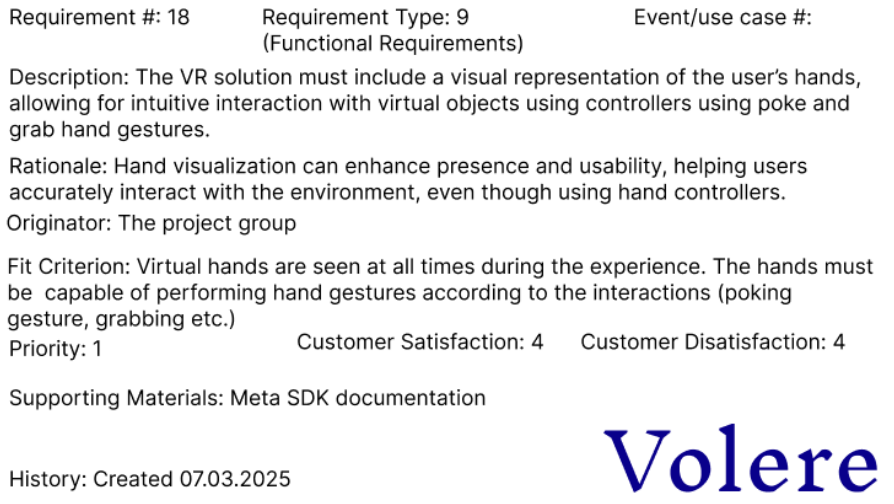
Fit Criterion: The user will learn based on reliable and accurate references.

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 5

Supporting Materials:

History: Created 07.03.2025

Volere



Requirement #: 18 Requirement Type: 9 (Functional Requirements) Event/use case #:

Description: The VR solution must include a visual representation of the user's hands, allowing for intuitive interaction with virtual objects using controllers using poke and grab hand gestures.

Rationale: Hand visualization can enhance presence and usability, helping users accurately interact with the environment, even though using hand controllers.

Originator: The project group

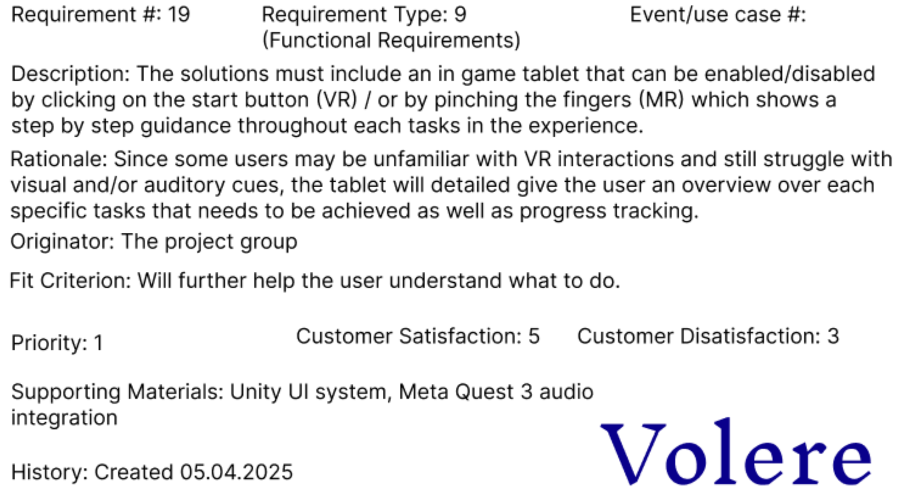
Fit Criterion: Virtual hands are seen at all times during the experience. The hands must be capable of performing hand gestures according to the interactions (poking gesture, grabbing etc.)

Priority: 1 Customer Satisfaction: 4 Customer Disatisfaction: 4

Supporting Materials: Meta SDK documentation

History: Created 07.03.2025

Volere



Requirement #: 19 Requirement Type: 9 (Functional Requirements) Event/use case #:

Description: The solutions must include an in game tablet that can be enabled/disabled by clicking on the start button (VR) / or by pinching the fingers (MR) which shows a step by step guidance throughout each tasks in the experience.

Rationale: Since some users may be unfamiliar with VR interactions and still struggle with visual and/or auditory cues, the tablet will detailed give the user an overview over each specific tasks that needs to be achieved as well as progress tracking.

Originator: The project group

Fit Criterion: Will further help the user understand what to do.

Priority: 1 Customer Satisfaction: 5 Customer Disatisfaction: 3

Supporting Materials: Unity UI system, Meta Quest 3 audio integration

History: Created 05.04.2025

Volere

Appendix H

Thematic analysis - Iteration 1 & 2

Note: Due to the extensive length of the thematic analysis, the full documentation has been included in separate external files. Both thematic analysis from the VR and MR prototypes can be simply accessed via the following links:

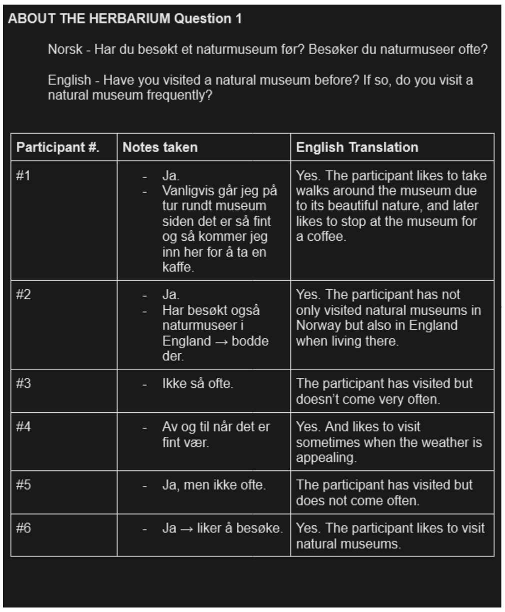
Thematic analysis VR Iteration 1 & 2

Thematic analysis MR Iteration 1 & 2

Appendix I

User interviews with six participants

To be conducted during week 11 in March of 2025: 14.03.2025 Took place at the Natural Museum and Botanical Garden with 6 participants Goal: Validate user requirements, user needs, user expectations, any interest in the topic and conceptualize any knowledge gaps. 14 Questions with 3 topics: herbarium, learning and technology. User interviews conducted in Norwegian, where notes where taken, documented and later translated to english.

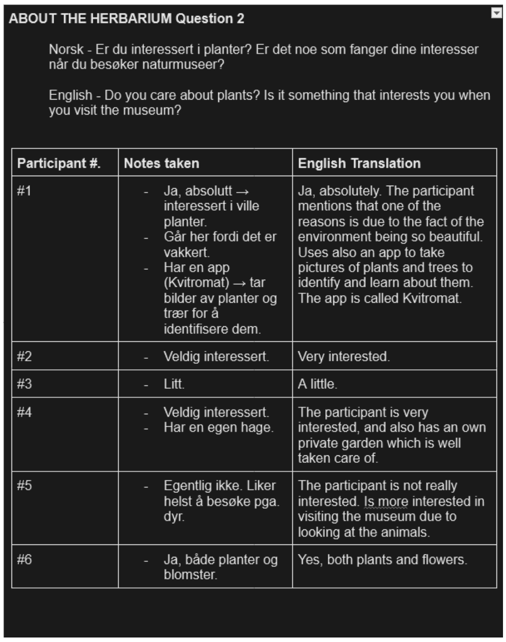


ABOUT THE HERBARIUM Question 1

Norsk - Har du besøkt et naturmuseum før? Besøker du naturmuseer ofte?

English - Have you visited a natural museum before? If so, do you visit a natural museum frequently?

Participant #.	Notes taken	English Translation
#1	- Ja. - Vanligvis går jeg på tur rundt museum siden det er så fint og så kommer jeg inn her for å ta en kaffe.	Yes. The participant likes to take walks around the museum due to its beautiful nature, and later likes to stop at the museum for a coffee.
#2	- Ja. - Har besøkt også naturmuseer i England → bodde der.	Yes. The participant has not only visited natural museums in Norway but also in England when living there.
#3	- Ikke så ofte.	The participant has visited but doesn't come very often.
#4	- Av og til når det er fint vær.	Yes. And likes to visit sometimes when the weather is appealing.
#5	- Ja, men ikke ofte.	The participant has visited but does not come often.
#6	- Ja → liker å besøke.	Yes. The participant likes to visit natural museums.

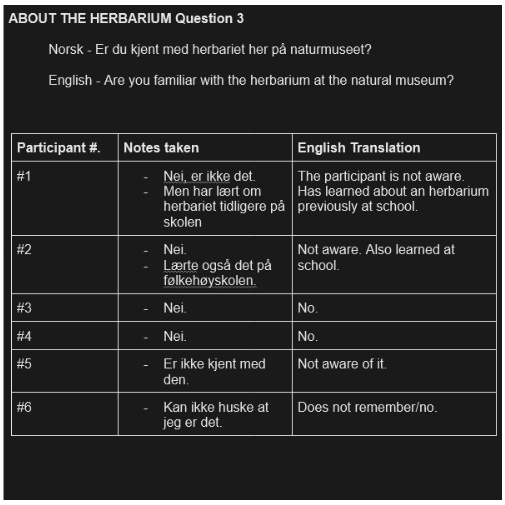


ABOUT THE HERBARIUM Question 2

Norsk - Er du interessert i planter? Er det noe som fanger dine interesser når du besøker naturmuseer?

English - Do you care about plants? Is it something that interests you when you visit the museum?

Participant #.	Notes taken	English Translation
#1	- Ja, absolutt → interessert i ville planter. - Går her fordi det er vakkert. - Har en app (Kvitromat) → tar bilder av planter og trær for å identifisere dem.	Ja, absolutely. The participant mentions that one of the reasons is due to the fact of the environment being so beautiful. Uses also an app to take pictures of plants and trees to identify and learn about them. The app is called Kvitromat.
#2	- Veldig interessert.	Very interested.
#3	- Litt.	A little.
#4	- Veldig interessert. - Har en egen hage.	The participant is very interested, and also has an own private garden which is well taken care of.
#5	- Egentlig ikke. Liker helst å besøke pga. dyr.	The participant is not really interested. Is more interested in visiting the museum due to looking at the animals.
#6	- Ja, både planter og blomster.	Yes, both plants and flowers.

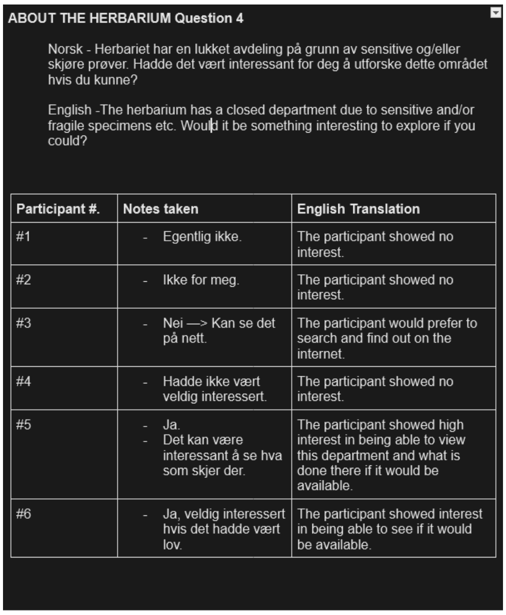


ABOUT THE HERBARIUM Question 3

Norsk - Er du kjent med herbariet her på naturmuseet?

English - Are you familiar with the herbarium at the natural museum?

Participant #.	Notes taken	English Translation
#1	- Nei, er ikke det. - Men har lært om herbariet tidligere på skolen	The participant is not aware. Has learned about an herbarium previously at school.
#2	- Nei. - Lærte også det på følkehøyskolen.	Not aware. Also learned at school.
#3	- Nei.	No.
#4	- Nei.	No.
#5	- Er ikke kjent med den.	Not aware of it.
#6	- Kan ikke huske at jeg er det.	Does not remember/no.

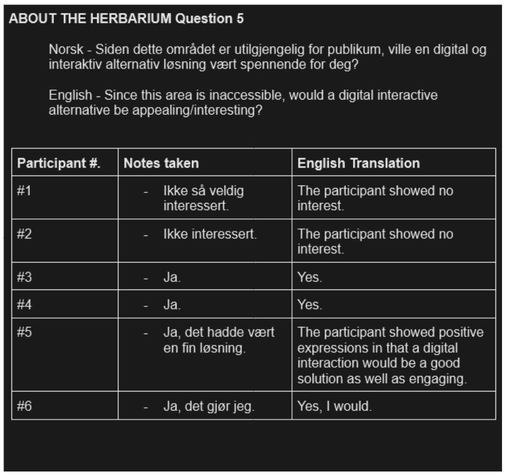


ABOUT THE HERBARIUM Question 4

Norsk - Herbariet har en lukket avdeling på grunn av sensitive og/eller skjøre prøver. Hadde det vært interessant for deg å utforske dette området hvis du kunne?

English -The herbarium has a closed department due to sensitive and/or fragile specimens etc. Would it be something interesting to explore if you could?

Participant #.	Notes taken	English Translation
#1	- Egentlig ikke.	The participant showed no interest.
#2	- Ikke for meg.	The participant showed no interest.
#3	- Nei —> Kan se det på nett.	The participant would prefer to search and find out on the internet.
#4	- Hadde ikke vært veldig interessert.	The participant showed no interest.
#5	- Ja. - Det kan være interessant å se hva som skjer der.	The participant showed high interest in being able to view this department and what is done there if it would be available.
#6	- Ja, veldig interessert hvis det hadde vært lov.	The participant showed interest in being able to see if it would be available.

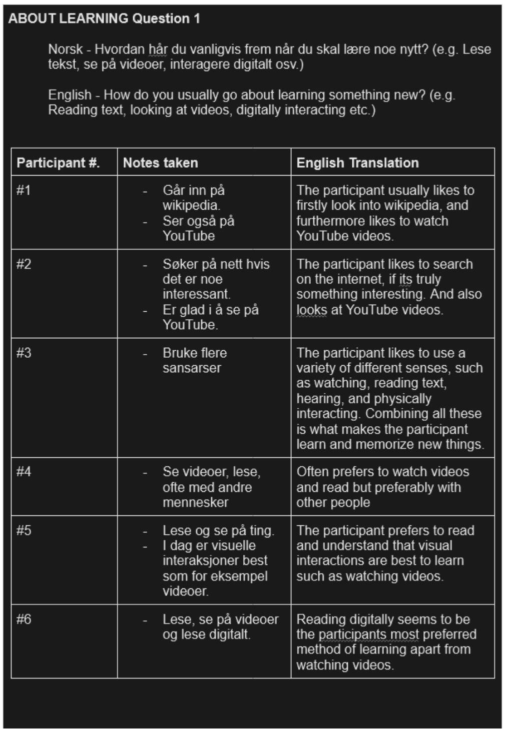


ABOUT THE HERBARIUM Question 5

Norsk - Siden dette området er utilgjengelig for publikum, ville en digital og interaktiv alternativ løsning vært spennende for deg?

English - Since this area is inaccessible, would a digital interactive alternative be appealing/interesting?

Participant #.	Notes taken	English Translation
#1	- Ikke så veldig interessert.	The participant showed no interest.
#2	- Ikke interessert.	The participant showed no interest.
#3	- Ja.	Yes.
#4	- Ja.	Yes.
#5	- Ja, det hadde vært en fin løsning.	The participant showed positive expressions in that a digital interaction would be a good solution as well as engaging.
#6	- Ja, det gjør jeg.	Yes, I would.

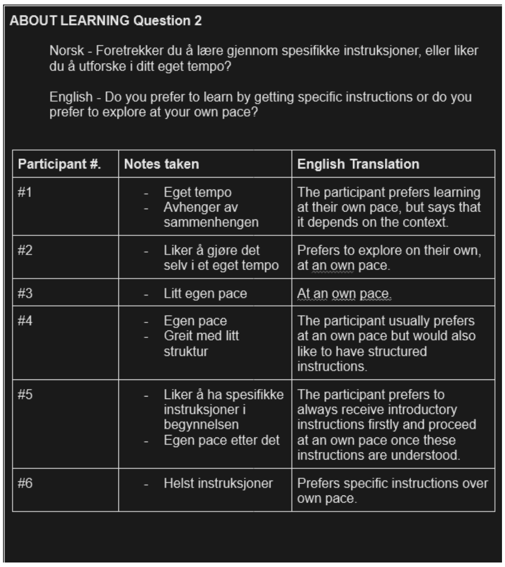


ABOUT LEARNING Question 1

Norsk - Hvordan hår du vanligvis frem når du skal lære noe nytt? (e.g. Lese tekst, se på videoer, interagere digitalt osv.)

English - How do you usually go about learning something new? (e.g. Reading text, looking at videos, digitally interacting etc.)

Participant #.	Notes taken	English Translation
#1	- Går inn på wikipedia. - Ser også på YouTube	The participant usually likes to firstly look into wikipedia, and furthermore likes to watch YouTube videos.
#2	- Søker på nett hvis det er noe interessant. - Er glad i å se på YouTube.	The participant likes to search on the internet, if its truly something interesting. And also looks at YouTube videos.
#3	- Bruke flere sansarser	The participant likes to use a variety of different senses, such as watching, reading text, hearing, and physically interacting. Combining all these is what makes the participant learn and memorize new things.
#4	- Se videoer, lese, ofte med andre mennesker	Often prefers to watch videos and read but preferably with other people
#5	- Lese og se på ting. - I dag er visuelle interaksjoner best som for eksempel videoer.	The participant prefers to read and understand that visual interactions are best to learn such as watching videos.
#6	- Lese, se på videoer og lese digitalt.	Reading digitally seems to be the participants most preferred method of learning apart from watching videos.

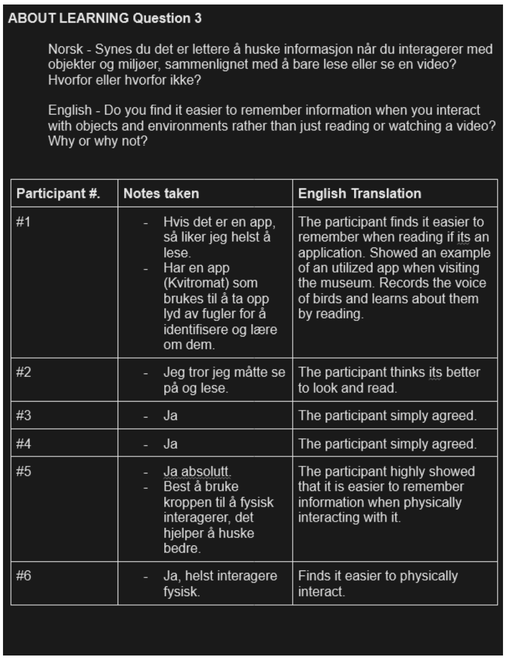


ABOUT LEARNING Question 2

Norsk - Foretrekker du å lære gjennom spesifikke instruksjoner, eller liker du å utforske i ditt eget tempo?

English - Do you prefer to learn by getting specific instructions or do you prefer to explore at your own pace?

Participant #.	Notes taken	English Translation
#1	- Eget tempo - Avhenger av sammenhengen	The participant prefers learning at their own pace, but says that it depends on the context.
#2	- Liker å gjøre det selv i et eget tempo	Prefers to explore on their own, at an own pace.
#3	- Litt egen pace	At an own pace.
#4	- Egen pace - Greit med litt struktur	The participant usually prefers at an own pace but would also like to have structured instructions.
#5	- Liker å ha spesifikke instruksjoner i begynnelsen - Egen pace etter det	The participant prefers to always receive introductory instructions firstly and proceed at an own pace once these instructions are understood.
#6	- Helst instruksjoner	Prefers specific instructions over own pace.

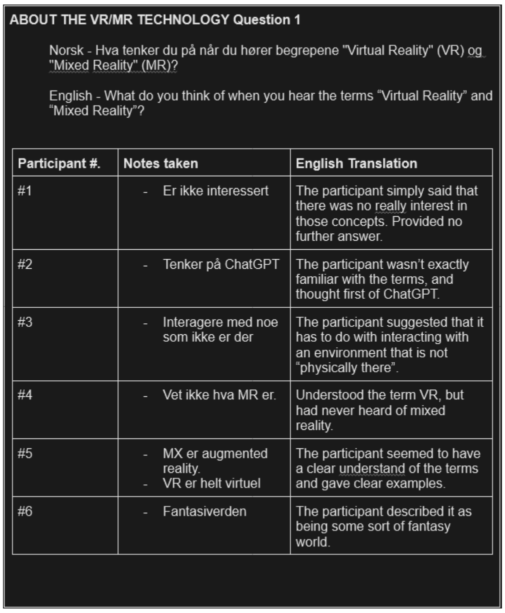


ABOUT LEARNING Question 3

Norsk - Synes du det er lettere å huske informasjon når du interagerer med objekter og miljøer, sammenlignet med å bare lese eller se en video? Hvorfor eller hvorfor ikke?

English - Do you find it easier to remember information when you interact with objects and environments rather than just reading or watching a video? Why or why not?

Participant #.	Notes taken	English Translation
#1	- Hvis det er en app, så liker jeg helst å lese. - Har en app (Kvitromat) som brukes til å ta opp lyd av fugler for å identifisere og lære om dem.	The participant finds it easier to remember when reading if its an application. Showed an example of an utilized app when visiting the museum. Records the voice of birds and learns about them by reading.
#2	- Jeg tror jeg måtte se på og lese.	The participant thinks its better to look and read.
#3	- Ja	The participant simply agreed.
#4	- Ja	The participant simply agreed.
#5	- Ja absolutt. - Best å bruke kroppen til å fysisk interagerer, det hjelper å huske bedre.	The participant highly showed that it is easier to remember information when physically interacting with it.
#6	- Ja, helst interagere fysisk.	Finds it easier to physically interact.

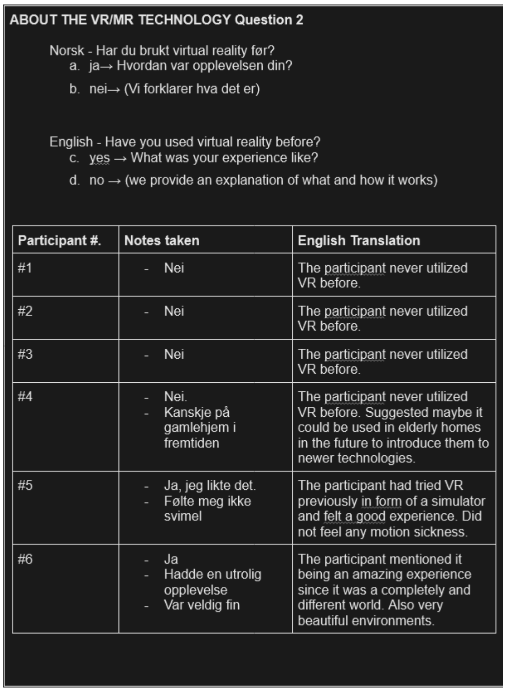


ABOUT THE VR/MR TECHNOLOGY Question 1

Norsk - Hva tenker du på når du hører begrepene "Virtual Reality" (VR) og "Mixed Reality" (MR)?

English - What do you think of when you hear the terms “Virtual Reality” and “Mixed Reality”?

Participant #.	Notes taken	English Translation
#1	- Er ikke interessert	The participant simply said that there was no really interest in those concepts. Provided no further answer.
#2	- Tenker på ChatGPT	The participant wasn’t exactly familiar with the terms, and thought first of ChatGPT.
#3	- Interagere med noe som ikke er der	The participant suggested that it has to do with interacting with an environment that is not “physically there”.
#4	- Vet ikke hva MR er.	Understood the term VR, but had never heard of mixed reality.
#5	- MX er augmented reality. - VR er helt virtuel	The participant seemed to have a clear understand of the terms and gave clear examples.
#6	- Fantasiverden	The participant described it as being some sort of fantasy world.

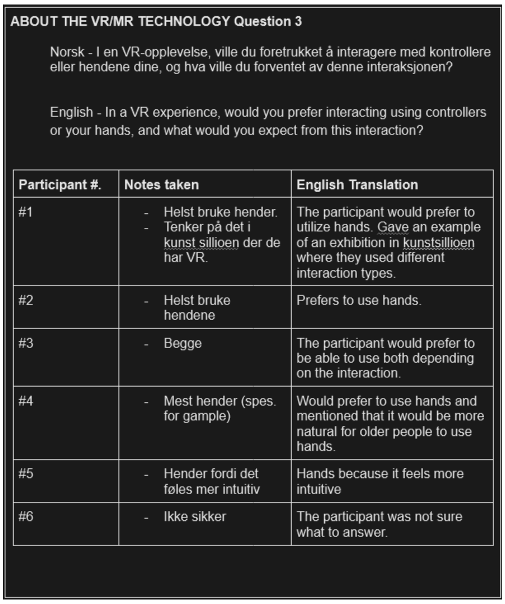


ABOUT THE VR/MR TECHNOLOGY Question 2

Norsk - Har du brukt virtual reality før?
  a. ja→ Hvordan var opplevelsen din?
  b. nei→ (Vi forklarer hva det er)

English - Have you used virtual reality before?
  c. yes → What was your experience like?
  d. no → (we provide an explanation of what and how it works)

Participant #.	Notes taken	English Translation
#1	- Nei	The participant never utilized VR before.
#2	- Nei	The participant never utilized VR before.
#3	- Nei	The participant never utilized VR before.
#4	- Nei. - Kanskje på gamlehjem i fremtiden	The participant never utilized VR before. Suggested maybe it could be used in elderly homes in the future to introduce them to newer technologies.
#5	- Ja, jeg likte det. - Følte meg ikke svimel	The participant had tried VR previously in form of a simulator and felt a good experience. Did not feel any motion sickness.
#6	- Ja - Hadde en utrolig opplevelse - Var veldig fin	The participant mentioned it being an amazing experience since it was a completely and different world. Also very beautiful environments.

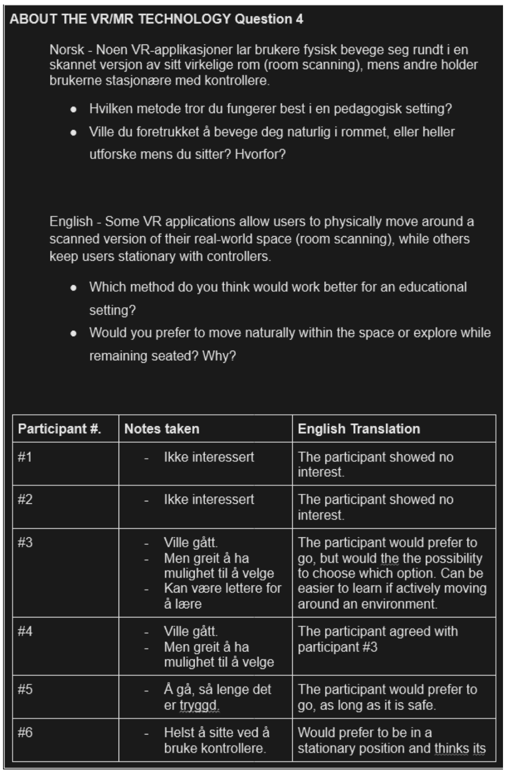


ABOUT THE VR/MR TECHNOLOGY Question 3

Norsk - I en VR-opplevelse, ville du foretrukket å interagere med kontrollere eller hendene dine, og hva ville du forventet av denne interaksjonen?

English - In a VR experience, would you prefer interacting using controllers or your hands, and what would you expect from this interaction?

Participant #.	Notes taken	English Translation
#1	- Helst bruke hender. - Tenker på det i kunst sillioen der de har VR.	The participant would prefer to utilize hands. Gave an example of an exhibition in kunstsillioen where they used different interaction types.
#2	- Helst bruke hendene	Prefers to use hands.
#3	- Begge	The participant would prefer to be able to use both depending on the interaction.
#4	- Mest hender (spes. for gample)	Would prefer to use hands and mentioned that it would be more natural for older people to use hands.
#5	- Hender fordi det føles mer intuitiv	Hands because it feels more intuitive
#6	- Ikke sikker	The participant was not sure what to answer.



ABOUT THE VR/MR TECHNOLOGY Question 4

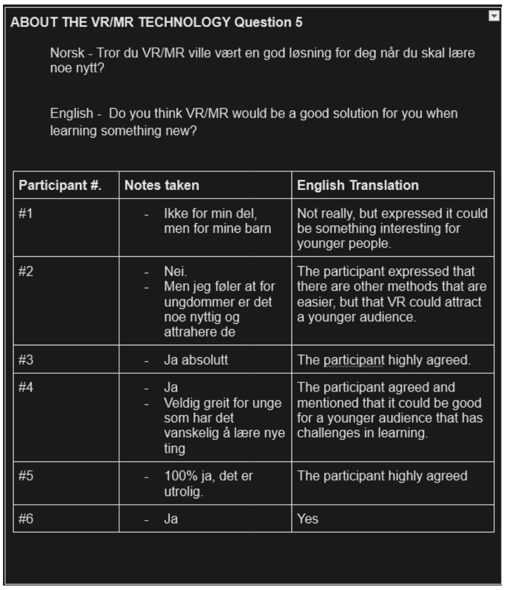
Norsk - Noen VR-applikasjoner lar brukere fysisk bevege seg rundt i en skannet versjon av sitt virkelige rom (room scanning), mens andre holder brukerne stasjonære med kontrollere.

- Hvilken metode tror du fungerer best i en pedagogisk setting?
- Ville du foretrukket å bevege deg naturlig i rommet, eller heller utforske mens du sitter? Hvorfor?

English - Some VR applications allow users to physically move around a scanned version of their real-world space (room scanning), while others keep users stationary with controllers.

- Which method do you think would work better for an educational setting?
- Would you prefer to move naturally within the space or explore while remaining seated? Why?

Participant #.	Notes taken	English Translation
#1	- Ikke interessert	The participant showed no interest.
#2	- Ikke interessert	The participant showed no interest.
#3	- Ville gått. - Men greit å ha mulighet til å velge - Kan være lettere for å lære	The participant would prefer to go, but would the the possibility to choose which option. Can be easier to learn if actively moving around an environment.
#4	- Ville gått. - Men greit å ha mulighet til å velge	The participant agreed with participant #3
#5	- Å gå, så lenge det er tryggd.	The participant would prefer to go, as long as it is safe.
#6	- Helst å sitte ved å bruke kontrollere.	Would prefer to be in a stationary position and thinks its

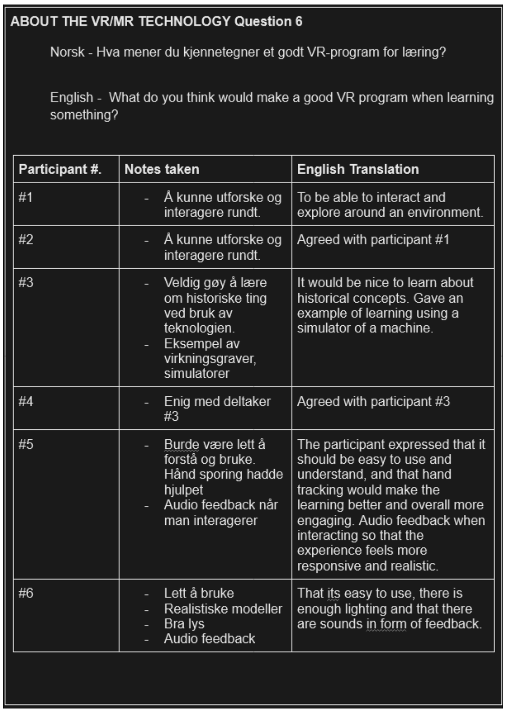


ABOUT THE VR/MR TECHNOLOGY Question 5

Norsk - Tror du VR/MR ville vært en god løsning for deg når du skal lære noe nytt?

English - Do you think VR/MR would be a good solution for you when learning something new?

Participant #.	Notes taken	English Translation
#1	- Ikke for min del, men for mine barn	Not really, but expressed it could be something interesting for younger people.
#2	- Nei. - Men jeg føler at for ungdommer er det noe nyttig og attrahere de	The participant expressed that there are other methods that are easier, but that VR could attract a younger audience.
#3	- Ja absolutt	The participant highly agreed.
#4	- Ja - Veldig greit for unge som har det vanskelig å lære nye ting	The participant agreed and mentioned that it could be good for a younger audience that has challenges in learning.
#5	- 100% ja, det er utrolig.	The participant highly agreed
#6	- Ja	Yes



ABOUT THE VR/MR TECHNOLOGY Question 6

Norsk - Hva mener du kjennetegner et godt VR-program for læring?

English - What do you think would make a good VR program when learning something?

Participant #.	Notes taken	English Translation
#1	- Å kunne utforske og interagere rundt.	To be able to interact and explore around an environment.
#2	- Å kunne utforske og interagere rundt.	Agreed with participant #1
#3	- Veldig gøy å lære om historiske ting ved bruk av teknologien. - Eksempel av virkningsgraver, simulatorer	It would be nice to learn about historical concepts. Gave an example of learning using a simulator of a machine.
#4	- Enig med deltaker #3	Agreed with participant #3
#5	- Burde være lett å forstå og bruke. Hånd sporing hadde hjulpet - Audio feedback når man interagerer	The participant expressed that it should be easy to use and understand, and that hand tracking would make the learning better and overall more engaging. Audio feedback when interacting so that the experience feels more responsive and realistic.
#6	- Lett å bruke - Realistiske modeller - Bra lys - Audio feedback	That its easy to use, there is enough lighting and that there are sounds in form of feedback.

Appendix J

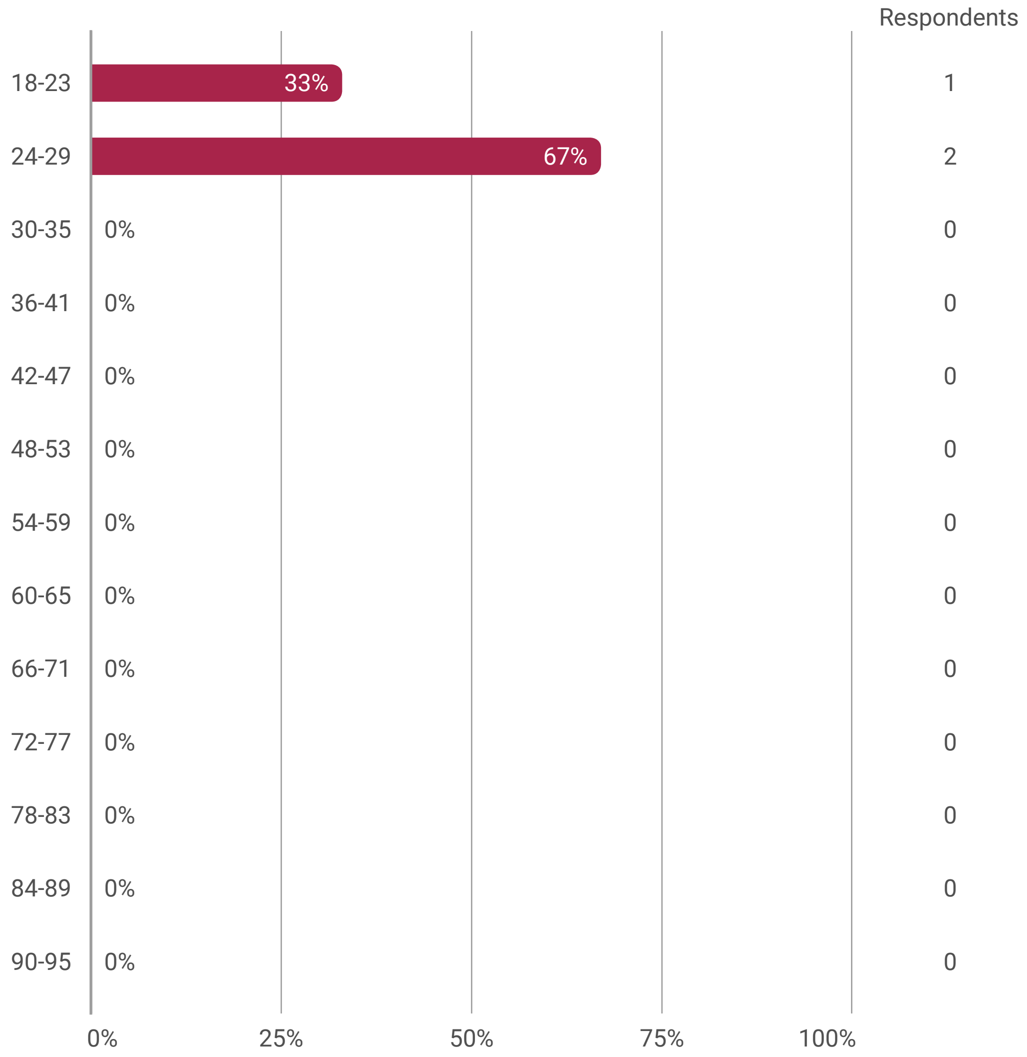
List of downloaded 3D assets & sound effects

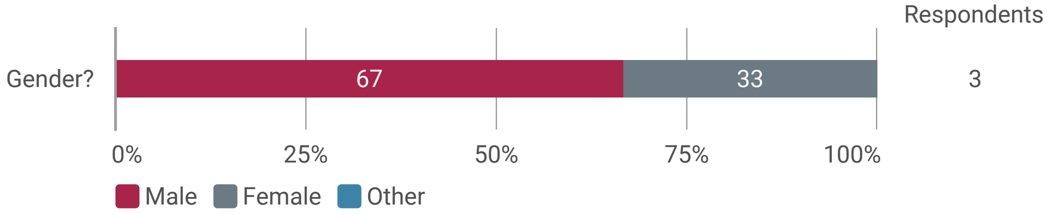
External 3D Assets	**Sound Effects**
Pilot Whale Model [30]	Elevator Moving [23]
Reception books [52]	Elevator Door Open/Close [42]
Reception plants [7]	UI Click [53]
Fire alarm indicator [4]	Hover UI [24]
Chair [7]	Task completed [32]
Computer desktop [7]	Temperature alarm [5]
Laptop [51]	Drying Sound Pressing room [28]
First aid cabinet [7]	Loading sound [10]
Fire alarm sprinkler [65]	
Lamp [7]	
Receptionist character [1]	
Bathroom door [7]	
Wall socket [7]	
Coca Cola Vending Machine [64]	
Fire extinguisher [20]	
Security camera [7]	
LAB Shoes [78]	
Tweezer [86]	
Generators in generator room [7]	

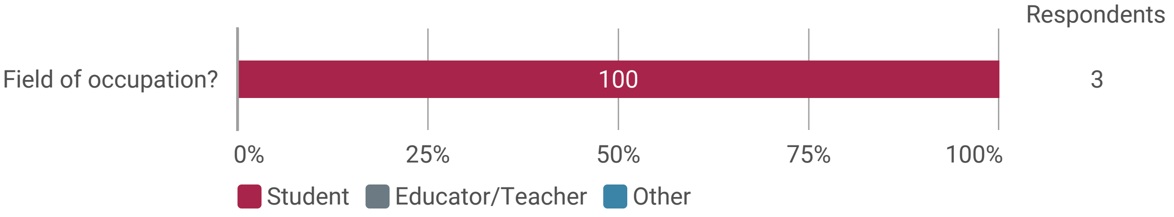
Appendix K

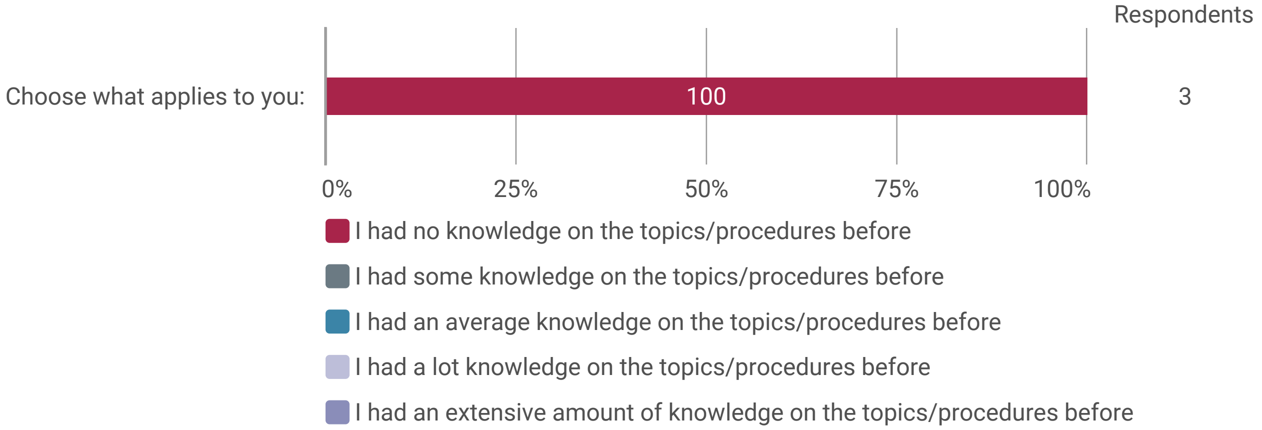
Questionnaire findings: Iteration 1 - VR

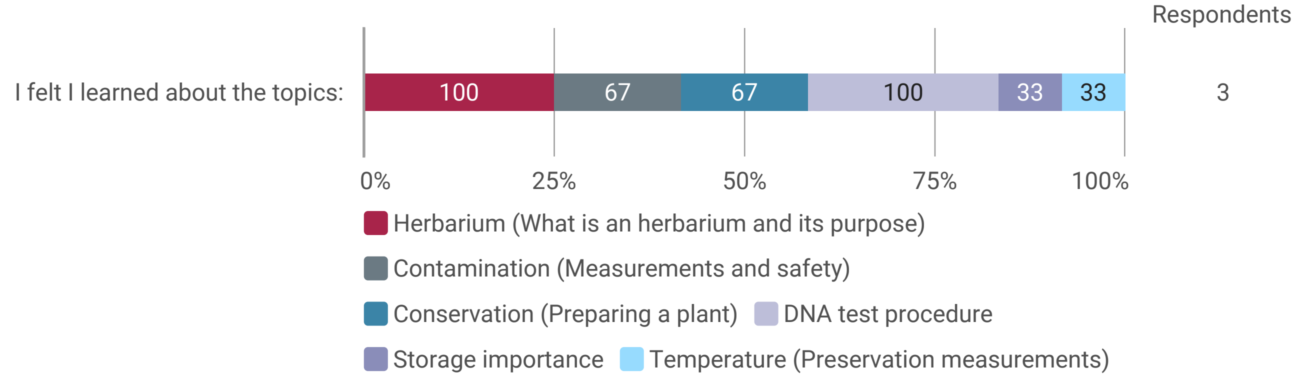
Age?

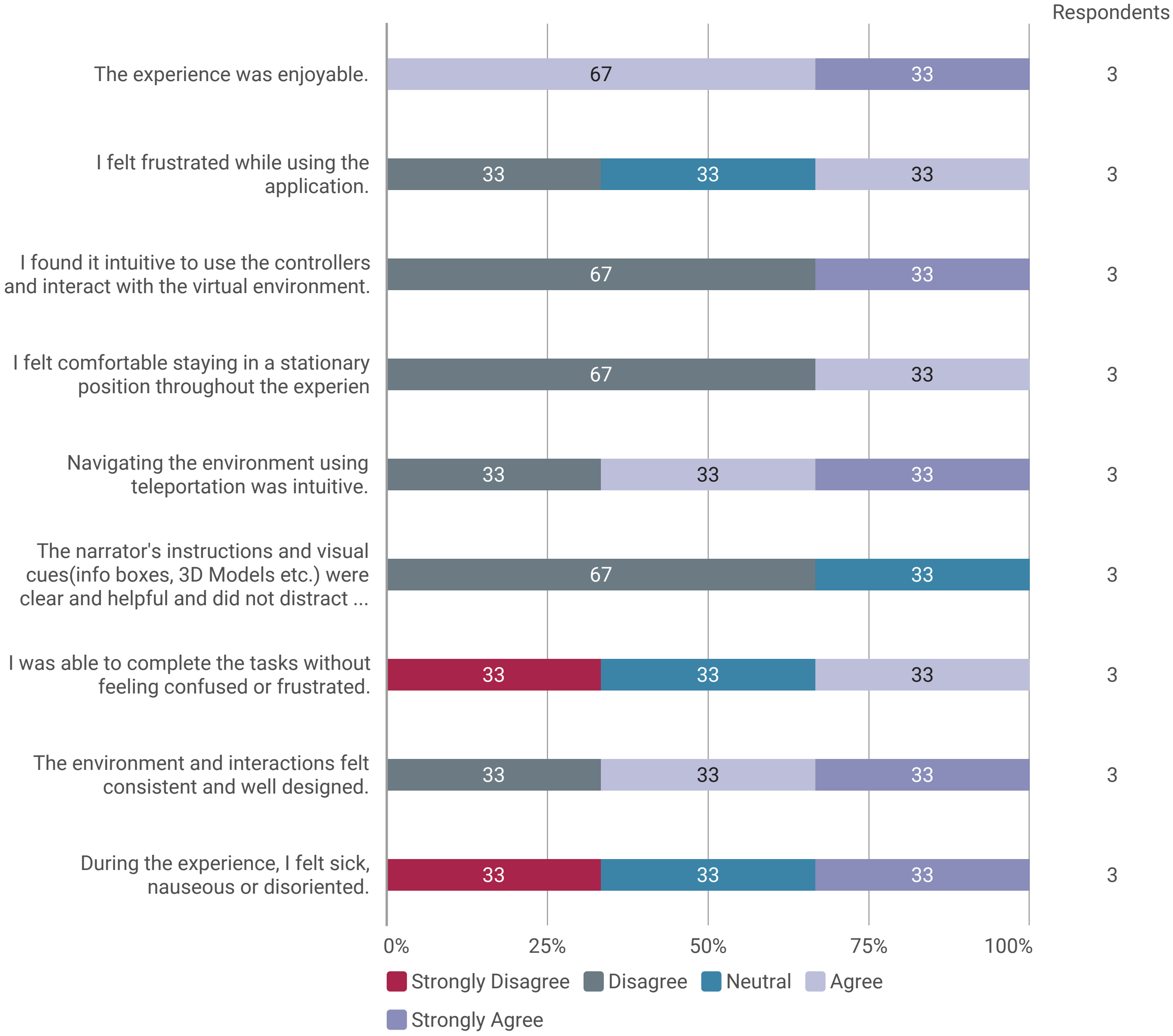

Respondents
18-23
33%
1
24-29
67%
2
30-35
0%
0
36-41
0%
0
42-47
0%
0
48-53
0%
0
54-59
0%
0
60-65
0%
0
66-71
0%
0
72-77
0%
0
78-83
0%
0
84-89
0%
0
90-95
0%
0
0%
25%
50%
75%
100%

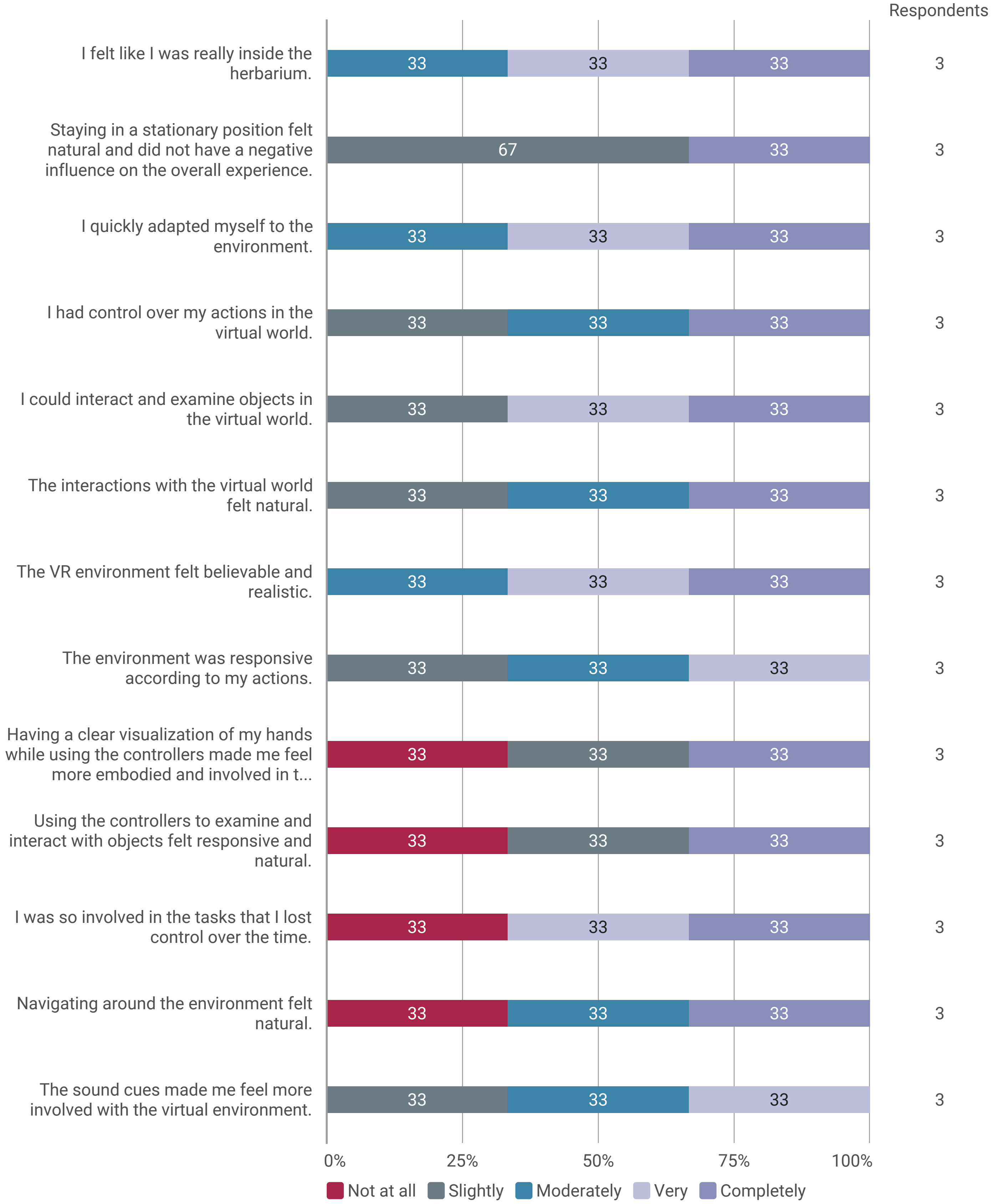

Respondents
Gender?
67
33
3
0%
25%
50%
75%
100%
Male
Female
Other

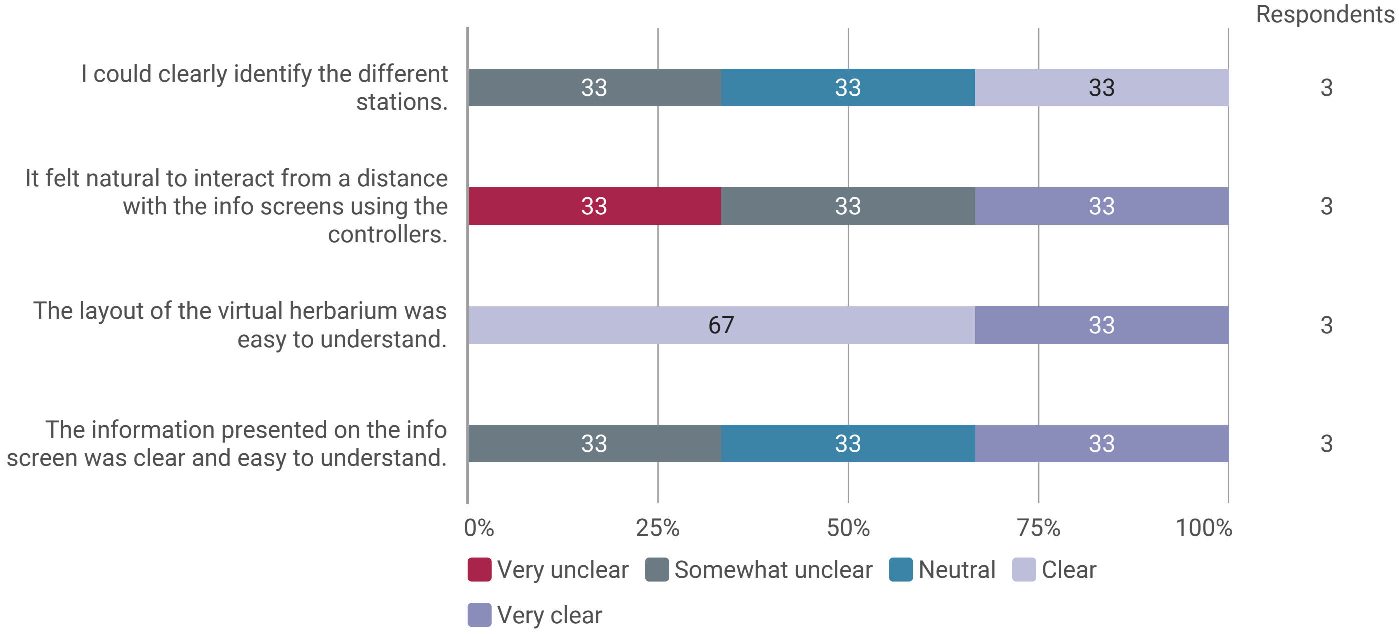

Respondents
Field of occupation?
100
3
0%
25%
50%
75%
100%
Student
Educator/Teacher
Other

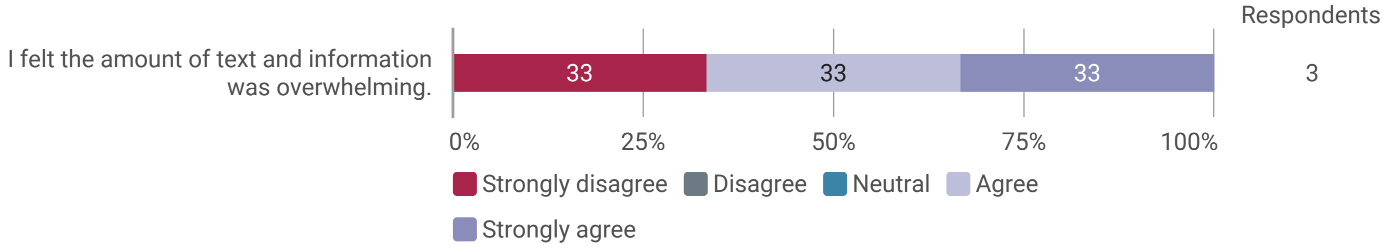

Respondents
Choose what applies to you:
100
3
0%
25%
50%
75%
100%
I had no knowledge on the topics/procedures before
I had some knowledge on the topics/procedures before
I had an average knowledge on the topics/procedures before
I had a lot knowledge on the topics/procedures before
I had an extensive amount of knowledge on the topics/procedures before

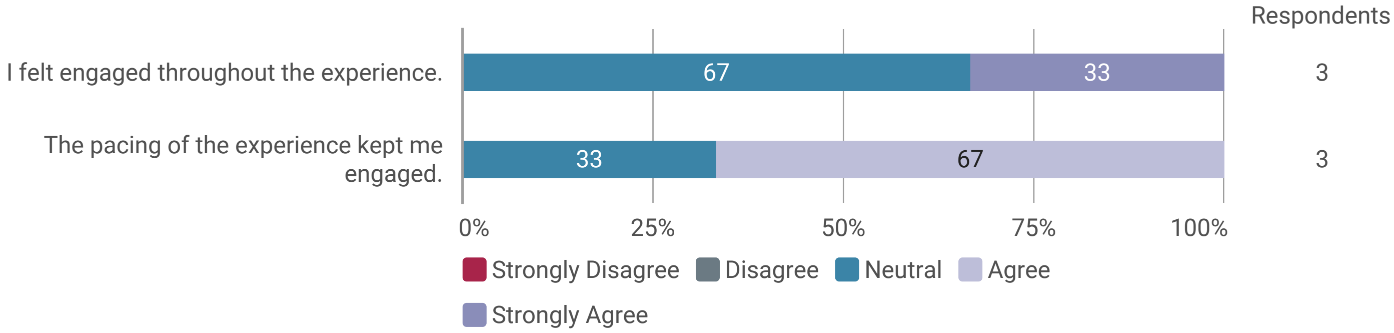

Respondents
I felt I learned about the topics:
100
67
67
100
33
33
3
0%
25%
50%
75%
100%
Herbarium (What is an herbarium and its purpose)
Contamination (Measurements and safety)
Conservation (Preparing a plant)
DNA test procedure
Storage importance
Temperature (Preservation measurements)

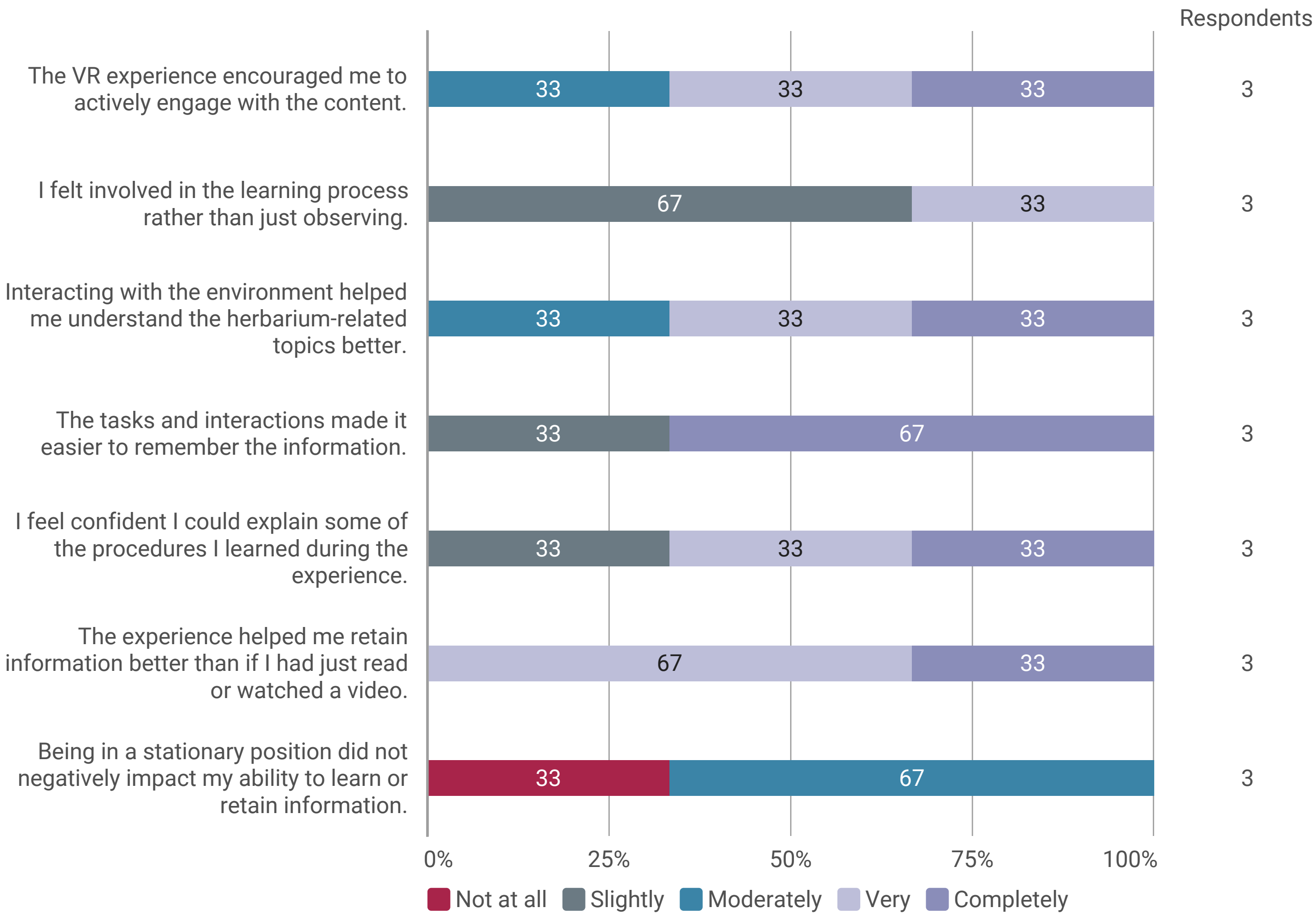

Respondents
The experience was enjoyable.
67
33
3
I felt frustrated while using the application.
33
33
33
3
I found it intuitive to use the controllers and interact with the virtual environment.
67
33
3
I felt comfortable staying in a stationary position throughout the experien
67
33
3
Navigating the environment using teleportation was intuitive.
33
33
33
3
The narrator's instructions and visual cues(info boxes, 3D Models etc.) were clear and helpful and did not distract ...
67
33
3
I was able to complete the tasks without feeling confused or frustrated.
33
33
33
3
The environment and interactions felt consistent and well designed.
33
33
33
3
During the experience, I felt sick, nauseous or disoriented.
33
33
33
3
0%
25%
50%
75%
100%
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree


Respondents
I felt like I was really inside the herbarium.
33
33
33
3
Staying in a stationary position felt natural and did not have a negative influence on the overall experience.
67
33
3
I quickly adapted myself to the environment.
33
33
33
3
I had control over my actions in the virtual world.
33
33
33
3
I could interact and examine objects in the virtual world.
33
33
33
3
The interactions with the virtual world felt natural.
33
33
33
3
The VR environment felt believable and realistic.
33
33
33
3
The environment was responsive according to my actions.
33
33
33
3
Having a clear visualization of my hands while using the controllers made me feel more embodied and involved in t...
33
33
33
3
Using the controllers to examine and interact with objects felt responsive and natural.
33
33
33
3
I was so involved in the tasks that I lost control over the time.
33
33
33
3
Navigating around the environment felt natural.
33
33
33
3
The sound cues made me feel more involved with the virtual environment.
33
33
33
3
0%
25%
50%
75%
100%
Not at all
Slightly
Moderately
Very
Completely


Respondents
I could clearly identify the different stations.
33
33
33
3
It felt natural to interact from a distance with the info screens using the controllers.
33
33
33
3
The layout of the virtual herbarium was easy to understand.
67
33
3
The information presented on the info screen was clear and easy to understand.
33
33
33
3
0%
25%
50%
75%
100%
Very unclear
Somewhat unclear
Neutral
Clear
Very clear


Respondents
I felt the amount of text and information was overwhelming.
33
33
33
3
0%
25%
50%
75%
100%
Strongly disagree
Disagree
Neutral
Agree
Strongly agree

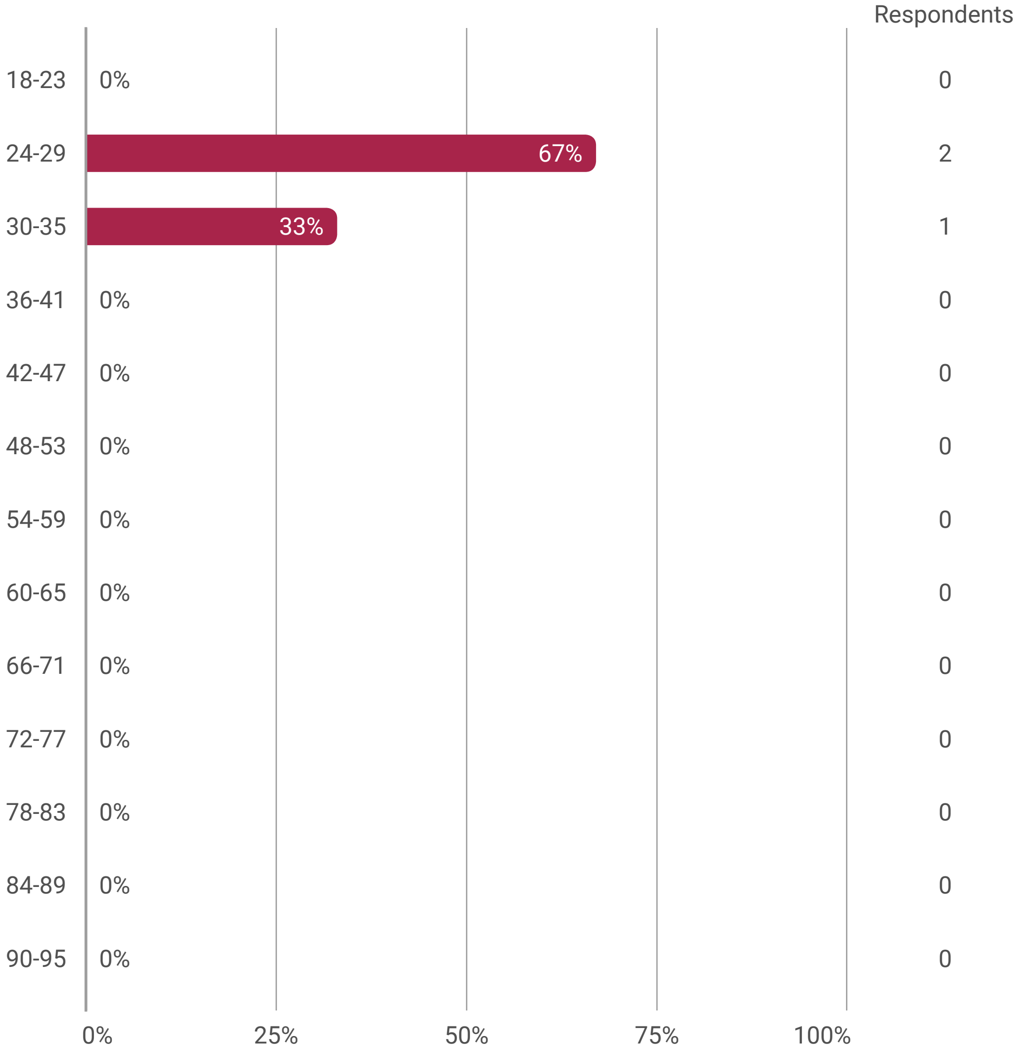

Respondents
I felt engaged throughout the experience.
67
33
3
The pacing of the experience kept me engaged.
33
67
3
0%
25%
50%
75%
100%
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree

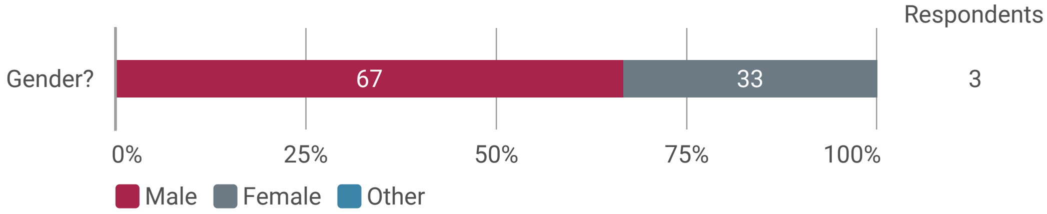

Respondents
The VR experience encouraged me to actively engage with the content.
33
33
33
3
I felt involved in the learning process rather than just observing.
67
33
3
Interacting with the environment helped me understand the herbarium-related topics better.
33
33
33
3
The tasks and interactions made it easier to remember the information.
33
67
3
I feel confident I could explain some of the procedures I learned during the experience.
33
33
33
3
The experience helped me retain information better than if I had just read or watched a video.
67
33
3
Being in a stationary position did not negatively impact my ability to learn or retain information.
33
67
3
0%
25%
50%
75%
100%
Not at all
Slightly
Moderately
Very
Completely

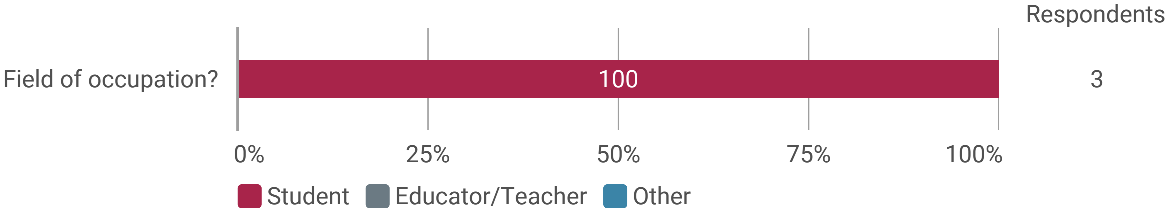
Appendix L

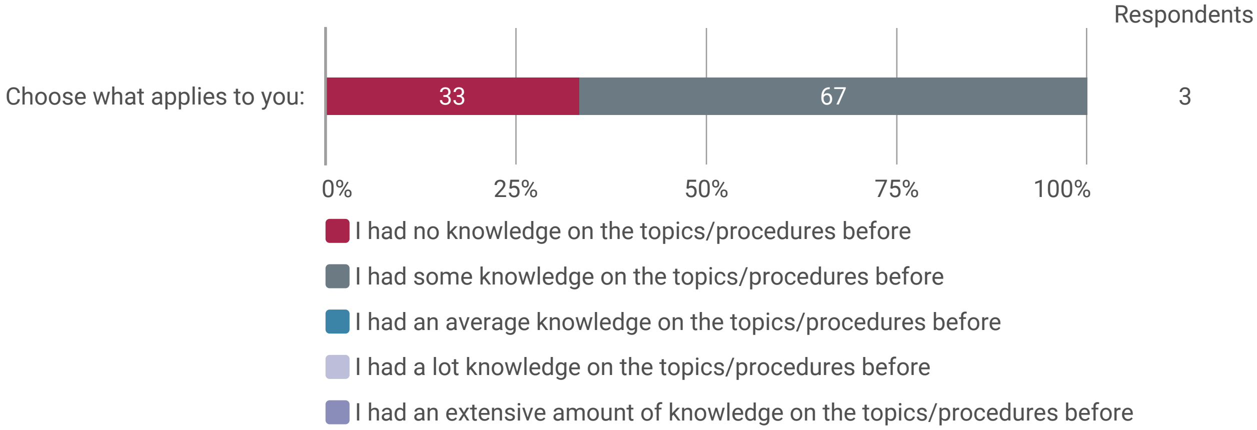
Questionnaire findings: Iteration 1 - MR

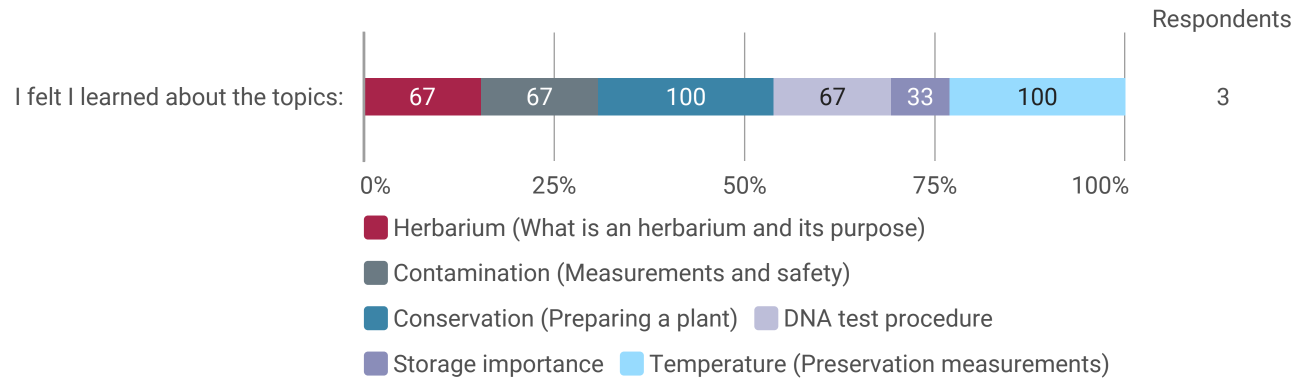
Age?

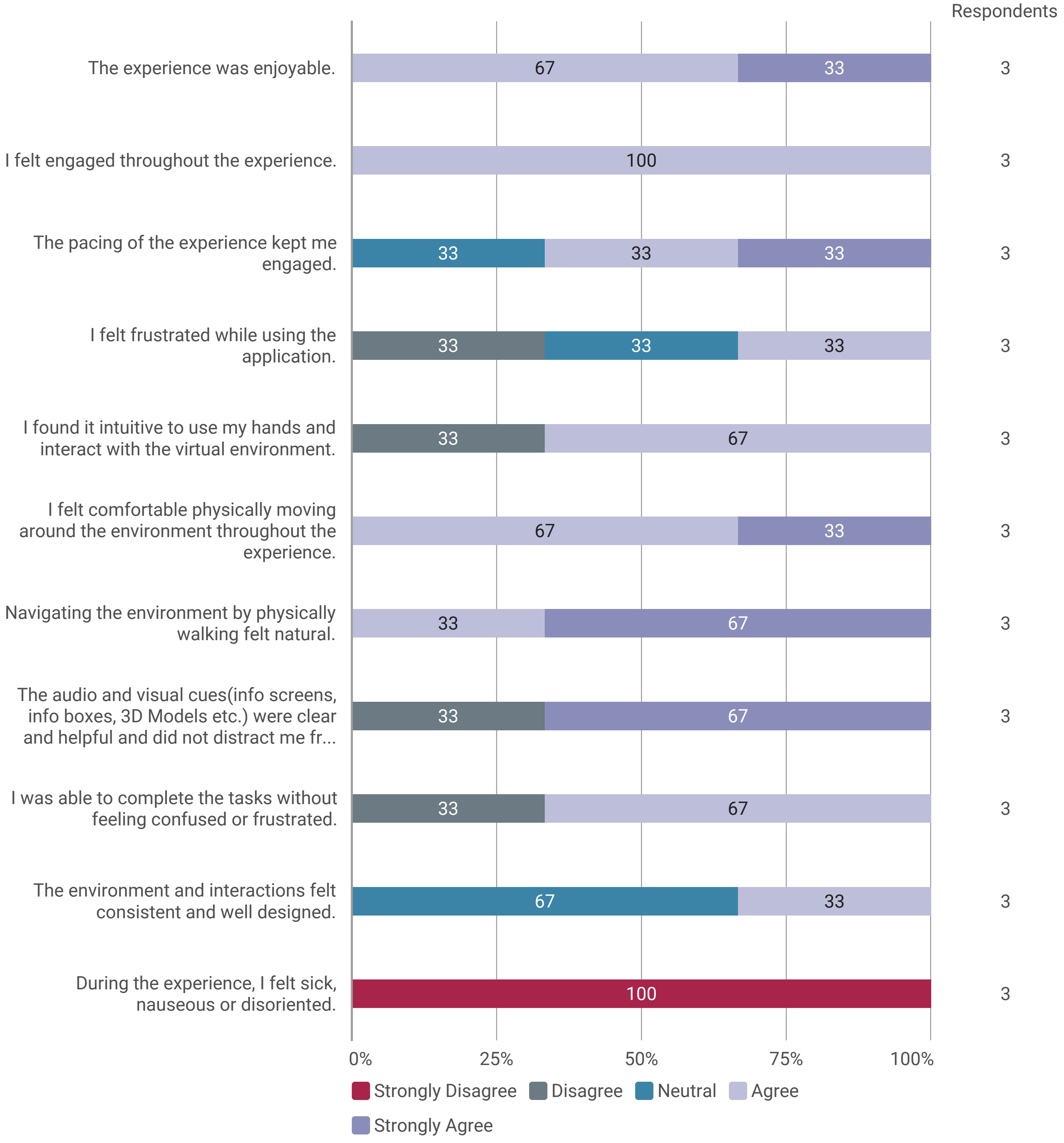

Respondents
18-23 0% 0
24-29 67% 2
30-35 33% 1
36-41 0% 0
42-47 0% 0
48-53 0% 0
54-59 0% 0
60-65 0% 0
66-71 0% 0
72-77 0% 0
78-83 0% 0
84-89 0% 0
90-95 0% 0
0%
25%
50%
75%
100%

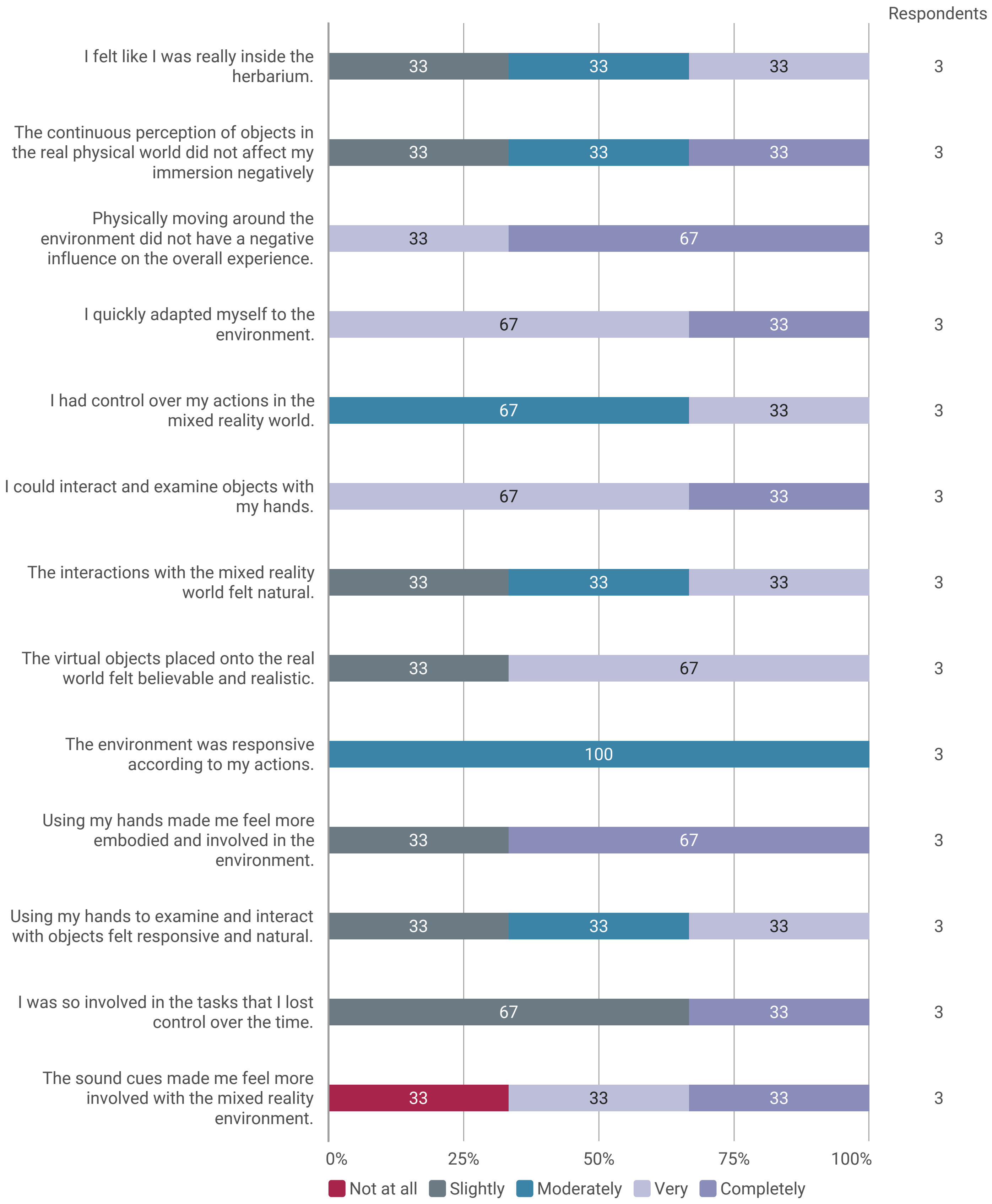

Respondents
Gender?
67
33
3
0%
25%
50%
75%
100%
Male
Female
Other

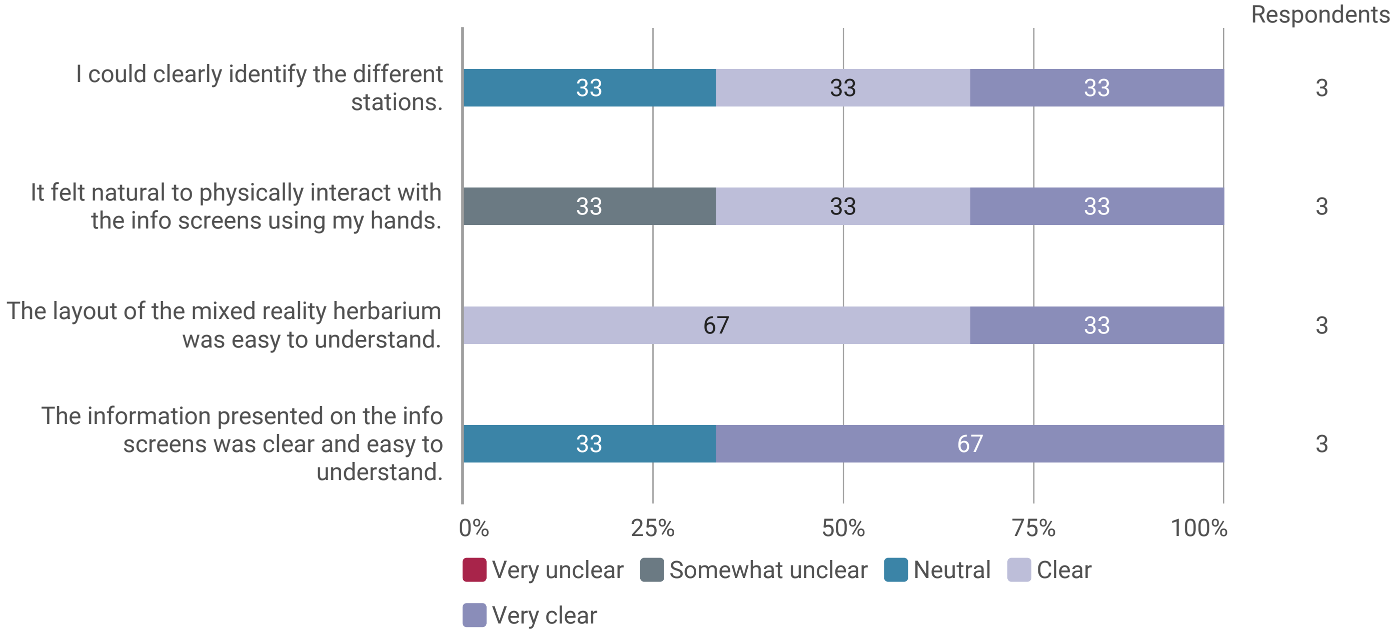

Respondents
Field of occupation?
100
3
0%
25%
50%
75%
100%
Student
Educator/Teacher
Other

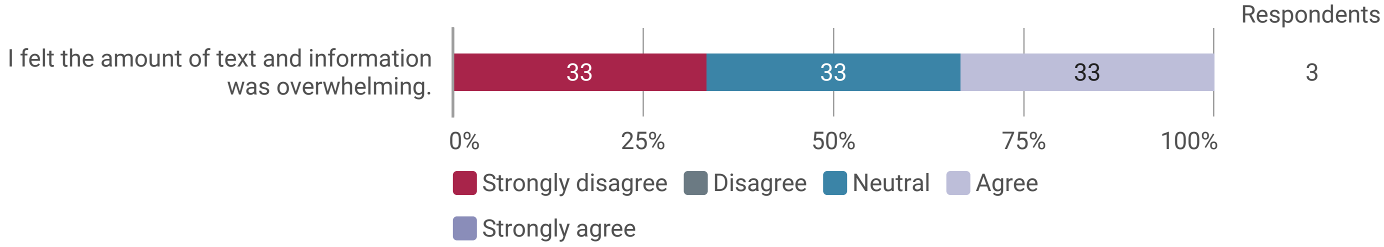

Respondents
Choose what applies to you:
33
67
3
0%
25%
50%
75%
100%
I had no knowledge on the topics/procedures before
I had some knowledge on the topics/procedures before
I had an average knowledge on the topics/procedures before
I had a lot knowledge on the topics/procedures before
I had an extensive amount of knowledge on the topics/procedures before

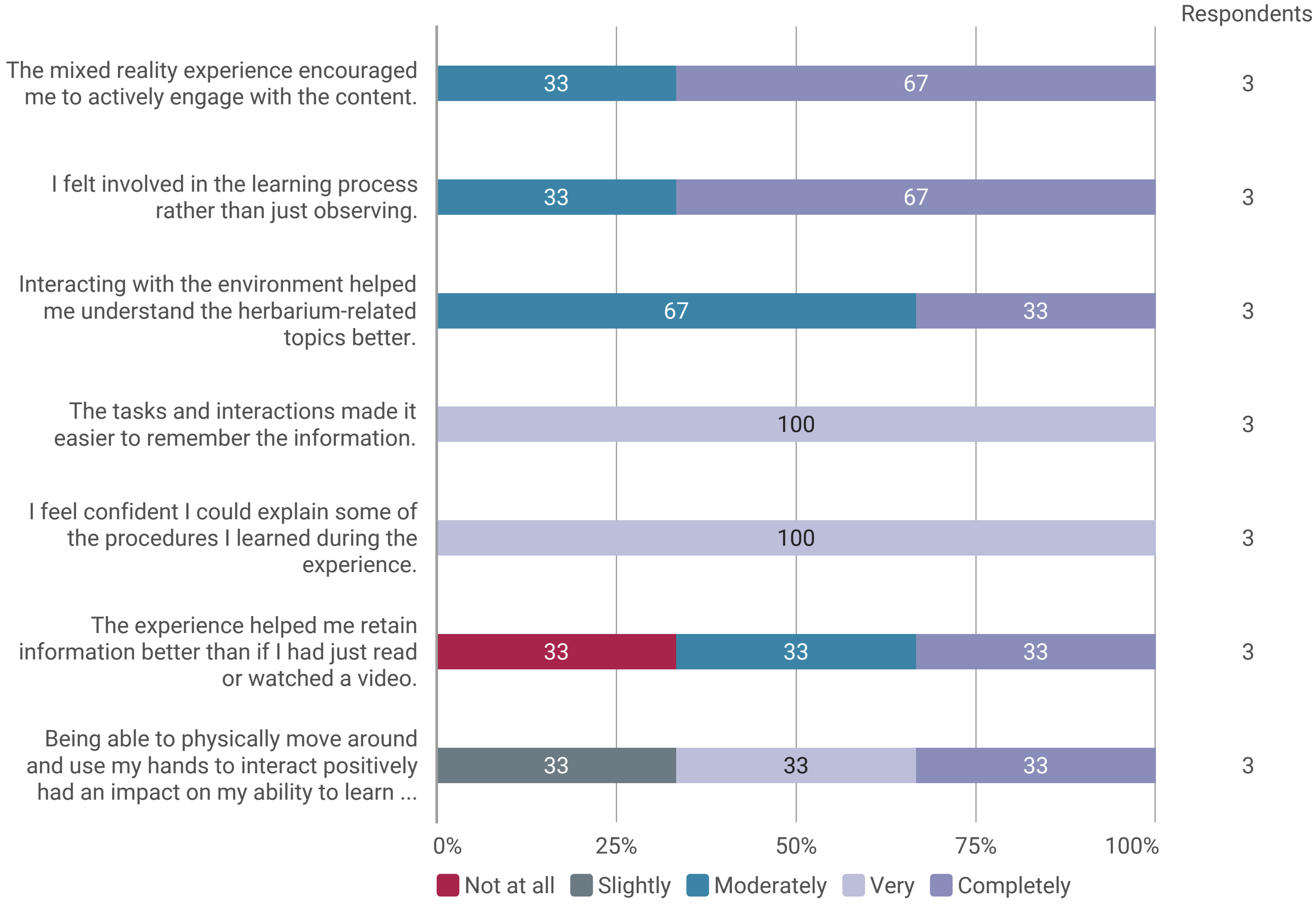

Respondents
I felt I learned about the topics:
67
67
100
67
33
100
3
0%
25%
50%
75%
100%
Herbarium (What is an herbarium and its purpose)
Contamination (Measurements and safety)
Conservation (Preparing a plant)
DNA test procedure
Storage importance
Temperature (Preservation measurements)


Respondents
The experience was enjoyable.
67
33
3
I felt engaged throughout the experience.
100
3
The pacing of the experience kept me engaged.
33
33
33
3
I felt frustrated while using the application.
33
33
33
3
I found it intuitive to use my hands and interact with the virtual environment.
33
67
3
I felt comfortable physically moving around the environment throughout the experience.
67
33
3
Navigating the environment by physically walking felt natural.
33
67
3
The audio and visual cues(info screens, info boxes, 3D Models etc.) were clear and helpful and did not distract me fr...
33
67
3
I was able to complete the tasks without feeling confused or frustrated.
33
67
3
The environment and interactions felt consistent and well designed.
67
33
3
During the experience, I felt sick, nauseous or disoriented.
100
3
0%
25%
50%
75%
100%
Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree


Respondents
I felt like I was really inside the herbarium.
33
33
33
3
The continuous perception of objects in the real physical world did not affect my immersion negatively
33
33
33
3
Physically moving around the environment did not have a negative influence on the overall experience.
33
67
3
I quickly adapted myself to the environment.
67
33
3
I had control over my actions in the mixed reality world.
67
33
3
I could interact and examine objects with my hands.
67
33
3
The interactions with the mixed reality world felt natural.
33
33
33
3
The virtual objects placed onto the real world felt believable and realistic.
33
67
3
The environment was responsive according to my actions.
100
3
Using my hands made me feel more embodied and involved in the environment.
33
67
3
Using my hands to examine and interact with objects felt responsive and natural.
33
33
33
3
I was so involved in the tasks that I lost control over the time.
67
33
3
The sound cues made me feel more involved with the mixed reality environment.
33
33
33
3
0%
25%
50%
75%
100%
Not at all
Slightly
Moderately
Very
Completely


Respondents
I could clearly identify the different stations.
33
33
33
3
It felt natural to physically interact with the info screens using my hands.
33
33
33
3
The layout of the mixed reality herbarium was easy to understand.
67
33
3
The information presented on the info screens was clear and easy to understand.
33
67
3
0%
25%
50%
75%
100%
Very unclear
Somewhat unclear
Neutral
Clear
Very clear

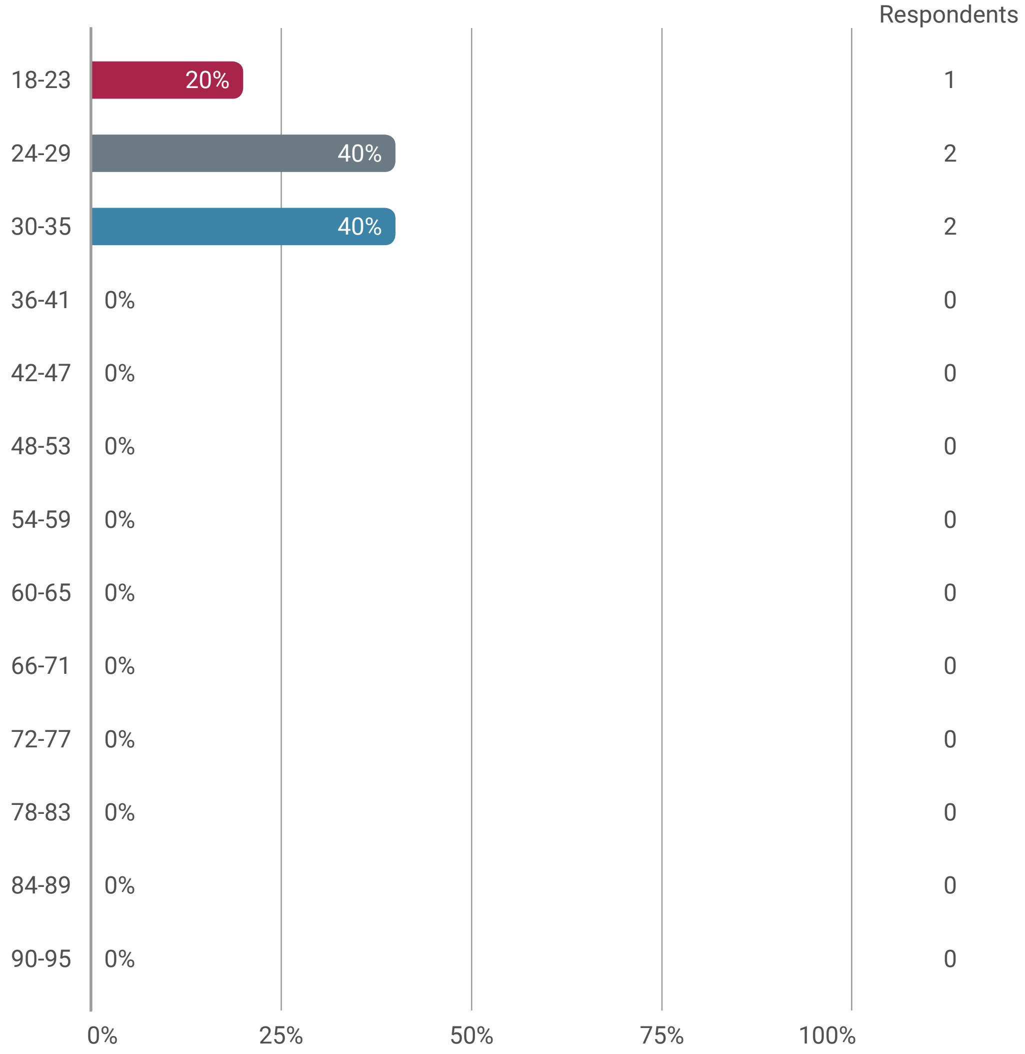

Respondents
I felt the amount of text and information was overwhelming.
33
33
33
3
0%
25%
50%
75%
100%
Strongly disagree
Disagree
Neutral
Agree
Strongly agree

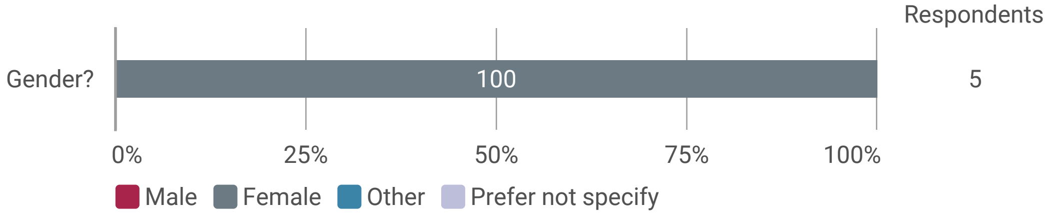

Respondents
The mixed reality experience encouraged me to actively engage with the content.
33
67
3
I felt involved in the learning process rather than just observing.
33
67
3
Interacting with the environment helped me understand the herbarium-related topics better.
67
33
3
The tasks and interactions made it easier to remember the information.
100
3
I feel confident I could explain some of the procedures I learned during the experience.
100
3
The experience helped me retain information better than if I had just read or watched a video.
33
33
33
3
Being able to physically move around and use my hands to interact positively had an impact on my ability to learn ...
33
33
33
3
0%
25%
50%
75%
100%
Not at all
Slightly
Moderately
Very
Completely

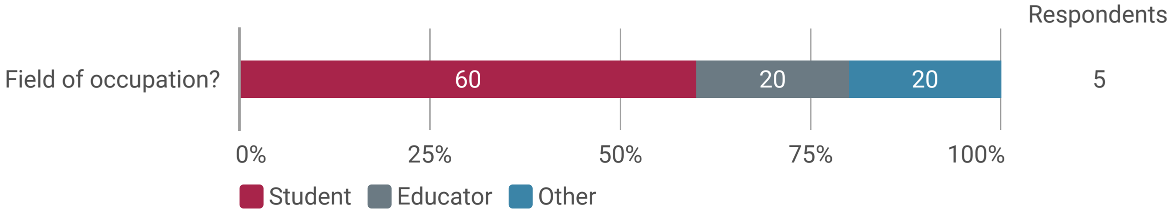
Appendix M

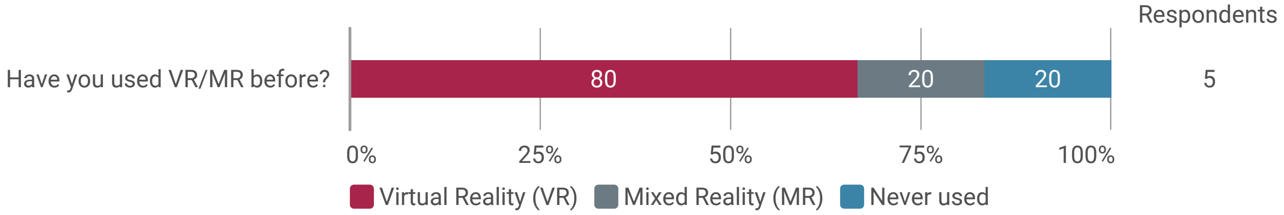
Questionnaire findings: Iteration 2 - VR

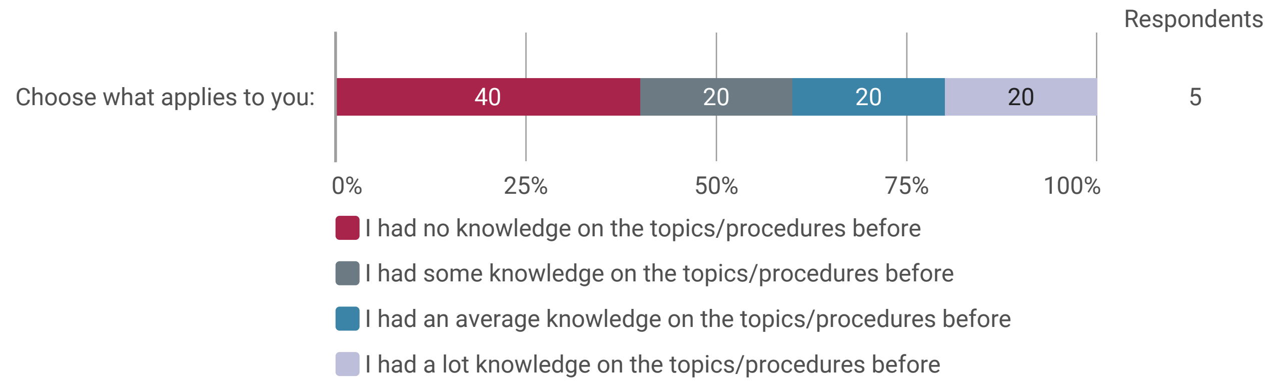
Age?

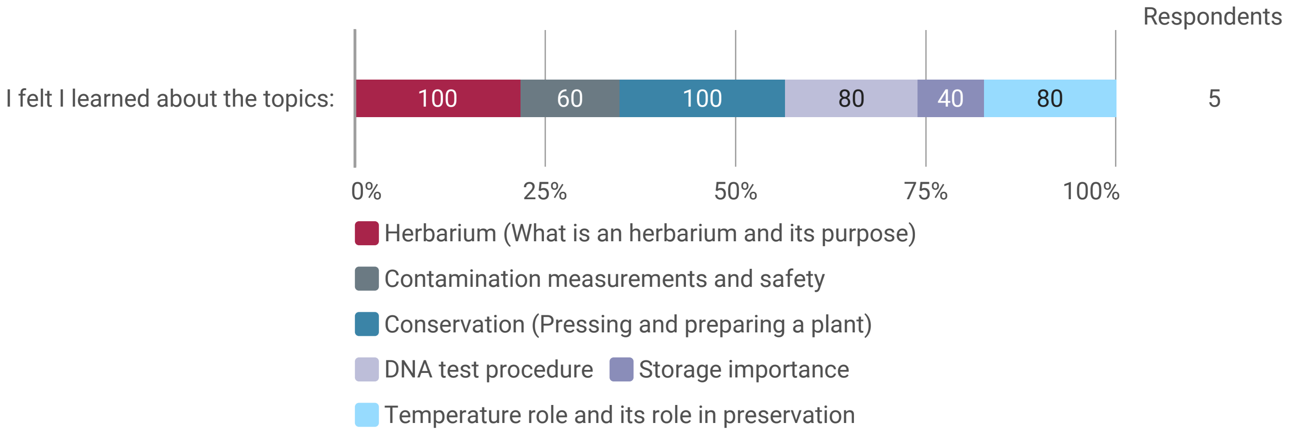

Respondents
18-23
20%
1
24-29
40%
2
30-35
40%
2
36-41
0%
0
42-47
0%
0
48-53
0%
0
54-59
0%
0
60-65
0%
0
66-71
0%
0
72-77
0%
0
78-83
0%
0
84-89
0%
0
90-95
0%
0
0%
25%
50%
75%
100%

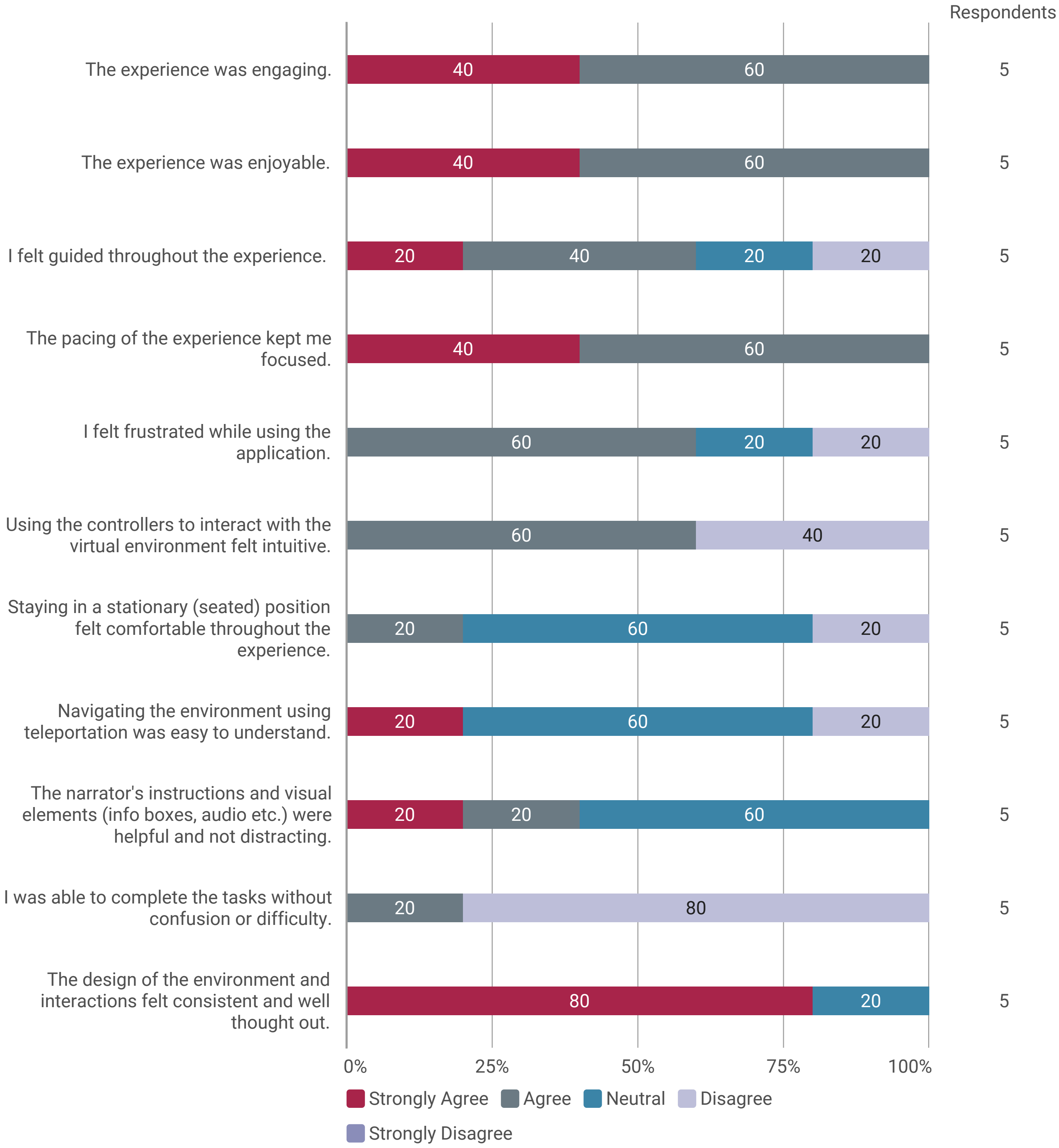

Respondents
Gender?
100
5
0%
25%
50%
75%
100%
Male
Female
Other
Prefer not specify

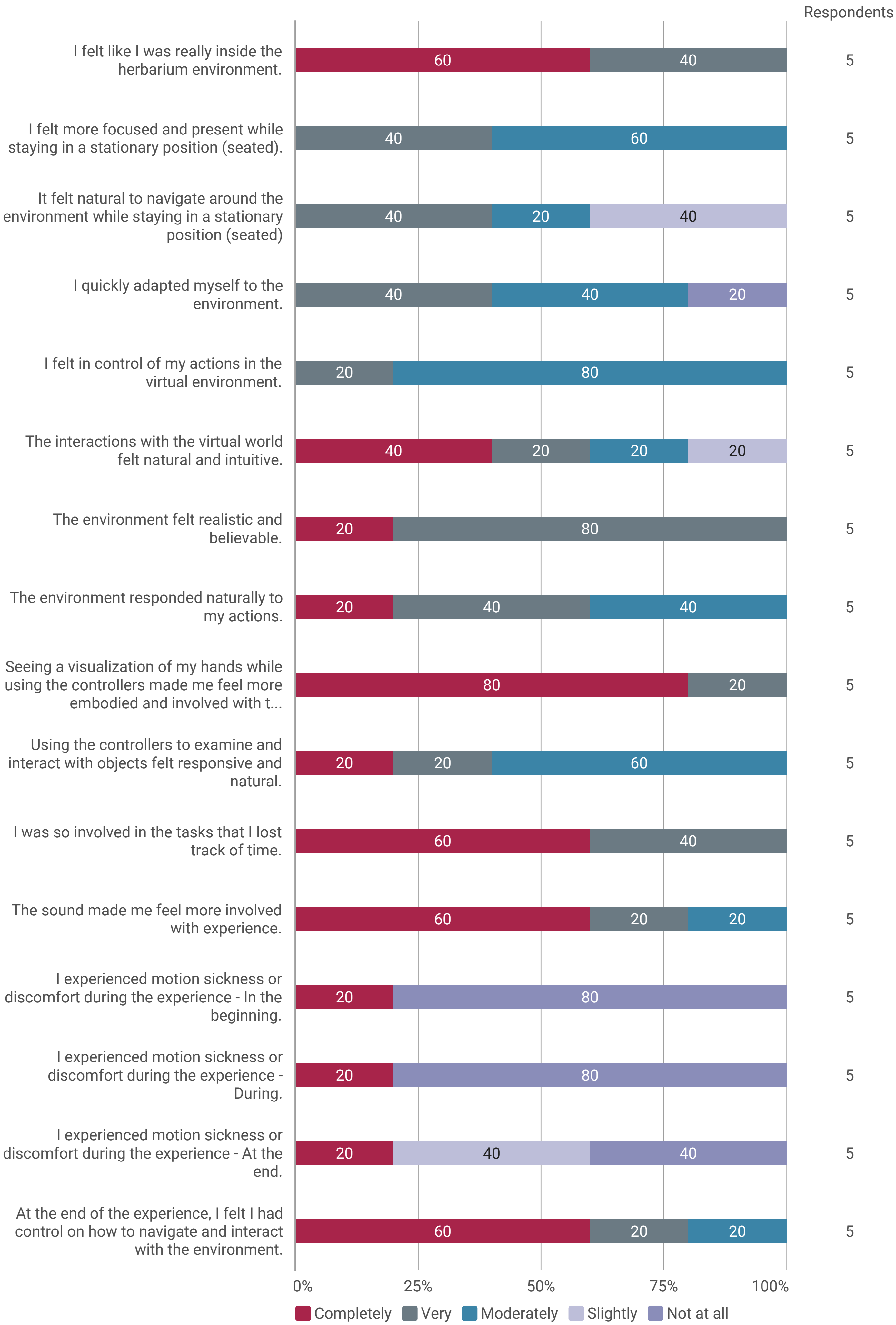

Respondents
Field of occupation?
60
20
20
5
0%
25%
50%
75%
100%
Student
Educator
Other

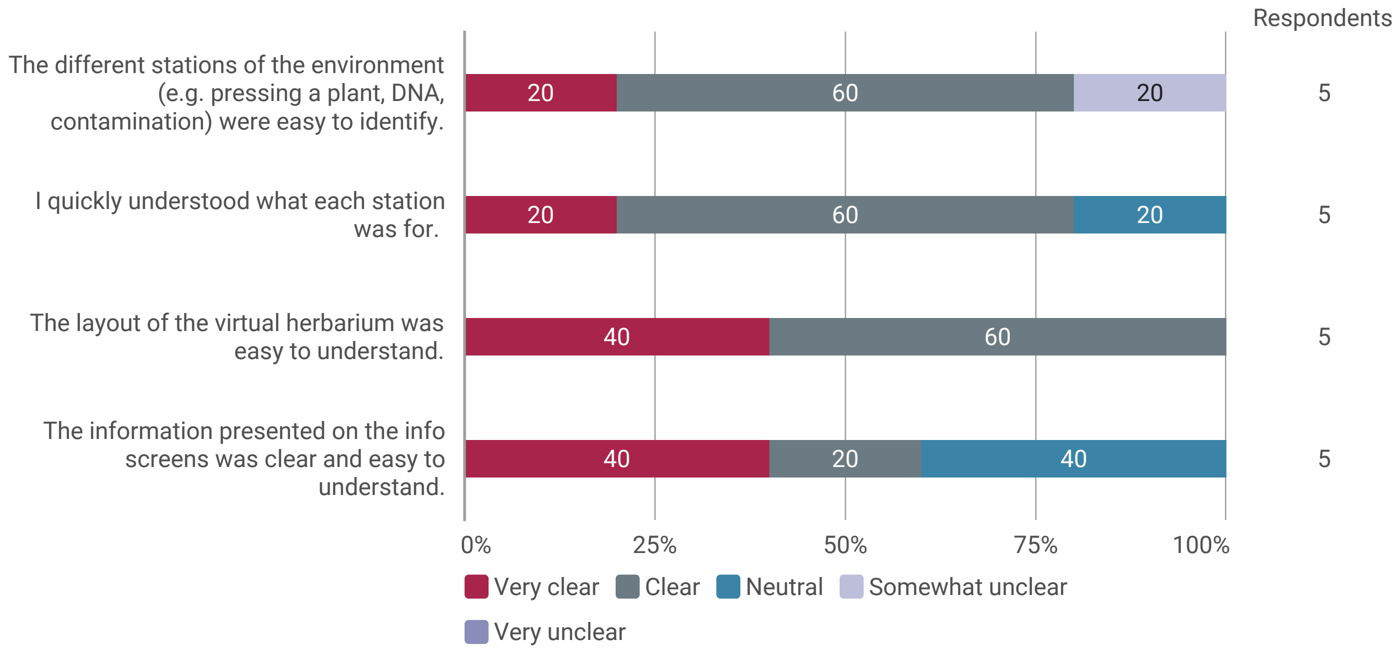

Respondents
Have you used VR/MR before?
80
20
20
5
0%
25%
50%
75%
100%
Virtual Reality (VR)
Mixed Reality (MR)
Never used

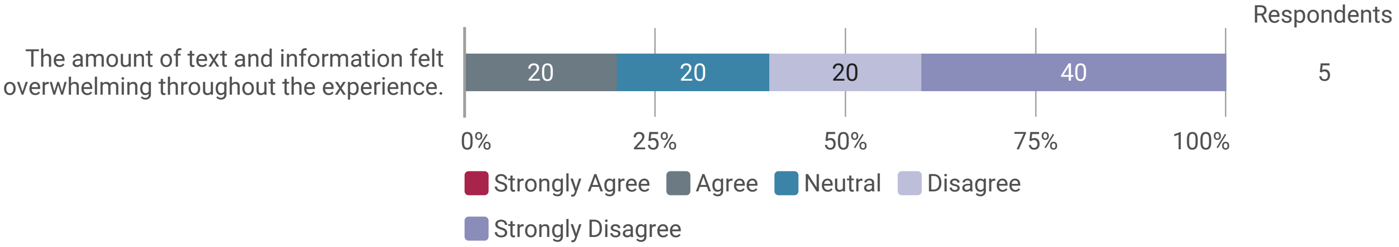

Respondents
Choose what applies to you:
40
20
20
20
5
0%
25%
50%
75%
100%
I had no knowledge on the topics/procedures before
I had some knowledge on the topics/procedures before
I had an average knowledge on the topics/procedures before
I had a lot knowledge on the topics/procedures before

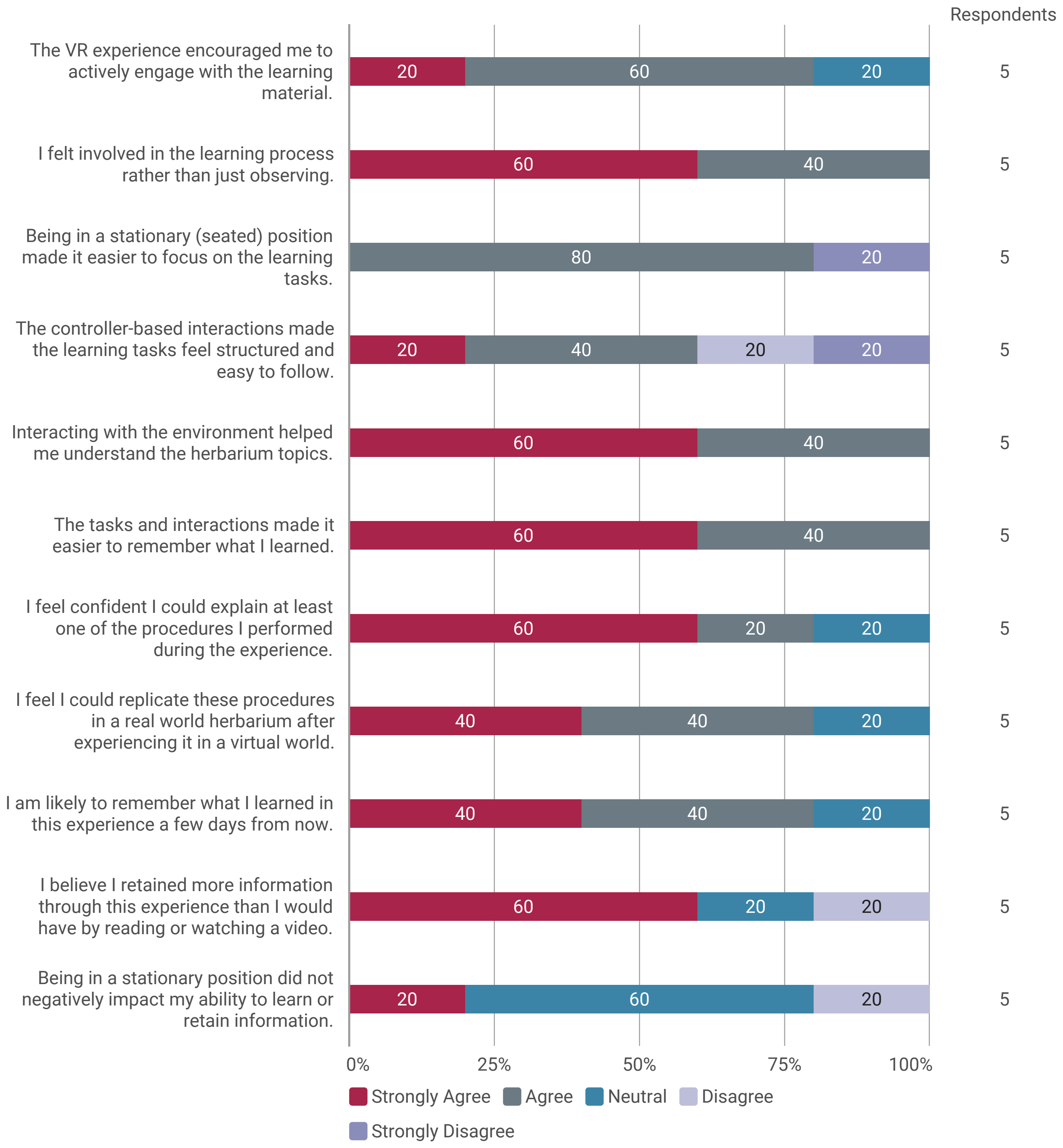

Respondents
I felt I learned about the topics:
100
60
100
80
40
80
5
0%
25%
50%
75%
100%
Herbarium (What is an herbarium and its purpose)
Contamination measurements and safety
Conservation (Pressing and preparing a plant)
DNA test procedure
Storage importance
Temperature role and its role in preservation


Respondents
The experience was engaging.
40
60
5
The experience was enjoyable.
40
60
5
I felt guided throughout the experience.
20
40
20
20
5
The pacing of the experience kept me focused.
40
60
5
I felt frustrated while using the application.
60
20
20
5
Using the controllers to interact with the virtual environment felt intuitive.
60
40
5
Staying in a stationary (seated) position felt comfortable throughout the experience.
20
60
20
5
Navigating the environment using teleportation was easy to understand.
20
60
20
5
The narrator's instructions and visual elements (info boxes, audio etc.) were helpful and not distracting.
20
20
60
5
I was able to complete the tasks without confusion or difficulty.
20
80
5
The design of the environment and interactions felt consistent and well thought out.
80
20
5
0%
25%
50%
75%
100%
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree


Respondents
I felt like I was really inside the herbarium environment.
60
40
5
I felt more focused and present while staying in a stationary position (seated).
40
60
5
It felt natural to navigate around the environment while staying in a stationary position (seated)
40
20
40
5
I quickly adapted myself to the environment.
40
40
20
5
I felt in control of my actions in the virtual environment.
20
80
5
The interactions with the virtual world felt natural and intuitive.
40
20
20
20
5
The environment felt realistic and believable.
20
80
5
The environment responded naturally to my actions.
20
40
40
5
Seeing a visualization of my hands while using the controllers made me feel more embodied and involved with t...
80
20
5
Using the controllers to examine and interact with objects felt responsive and natural.
20
20
60
5
I was so involved in the tasks that I lost track of time.
60
40
5
The sound made me feel more involved with experience.
60
20
20
5
I experienced motion sickness or discomfort during the experience - In the beginning.
20
80
5
I experienced motion sickness or discomfort during the experience - During.
20
80
5
I experienced motion sickness or discomfort during the experience - At the end.
20
40
40
5
At the end of the experience, I felt I had control on how to navigate and interact with the environment.
60
20
20
5
0%
25%
50%
75%
100%
Completely
Very
Moderately
Slightly
Not at all


Respondents
The different stations of the environment (e.g. pressing a plant, DNA, contamination) were easy to identify.
20
60
20
5
I quickly understood what each station was for.
20
60
20
5
The layout of the virtual herbarium was easy to understand.
40
60
5
The information presented on the info screens was clear and easy to understand.
40
20
40
5
0%
25%
50%
75%
100%
Very clear
Clear
Neutral
Somewhat unclear
Very unclear

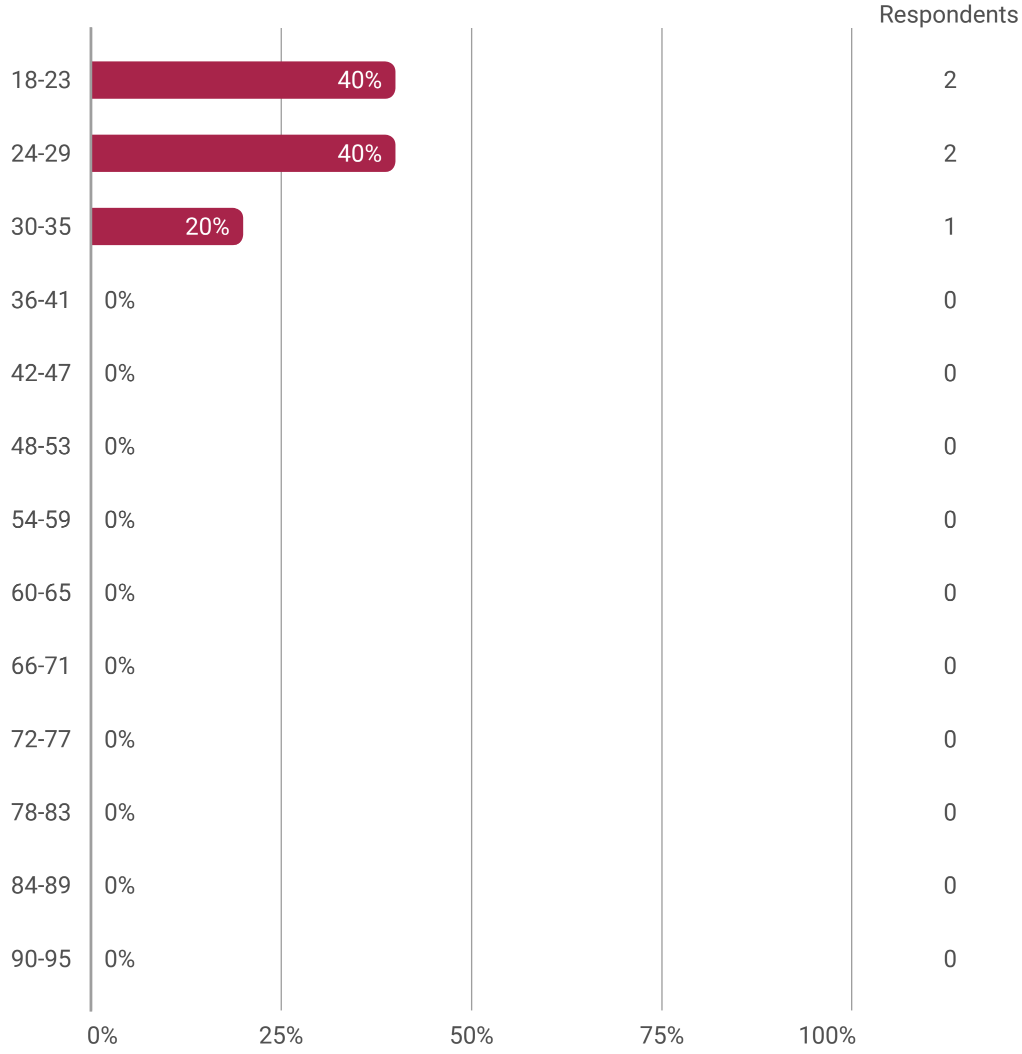

Respondents
The amount of text and information felt overwhelming throughout the experience.
20
20
20
40
5
0%
25%
50%
75%
100%
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

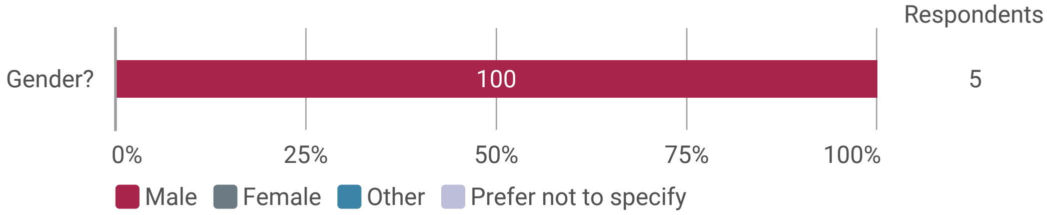

Respondents
The VR experience encouraged me to actively engage with the learning material.
20
60
20
5
I felt involved in the learning process rather than just observing.
60
40
5
Being in a stationary (seated) position made it easier to focus on the learning tasks.
80
20
5
The controller-based interactions made the learning tasks feel structured and easy to follow.
20
40
20
20
5
Interacting with the environment helped me understand the herbarium topics.
60
40
5
The tasks and interactions made it easier to remember what I learned.
60
40
5
I feel confident I could explain at least one of the procedures I performed during the experience.
60
20
20
5
I feel I could replicate these procedures in a real world herbarium after experiencing it in a virtual world.
40
40
20
5
I am likely to remember what I learned in this experience a few days from now.
40
40
20
5
I believe I retained more information through this experience than I would have by reading or watching a video.
60
20
20
5
Being in a stationary position did not negatively impact my ability to learn or retain information.
20
60
20
5
0%
25%
50%
75%
100%
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

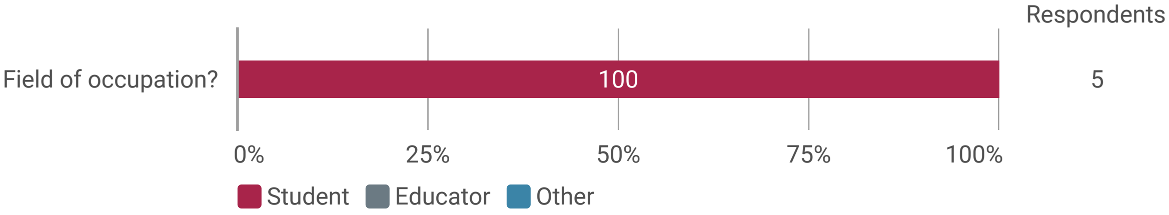
Appendix N

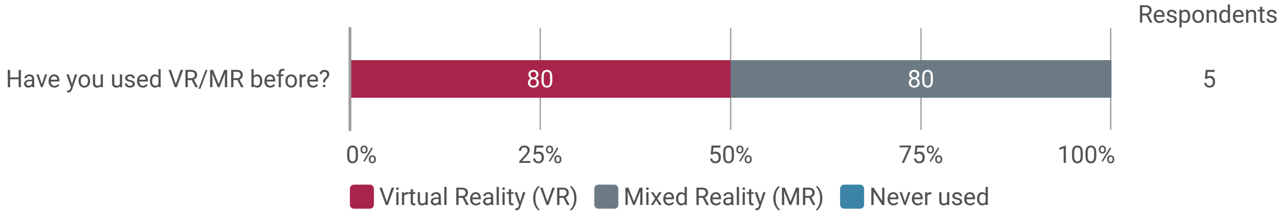
Questionnaire findings: Iteration 2 - MR

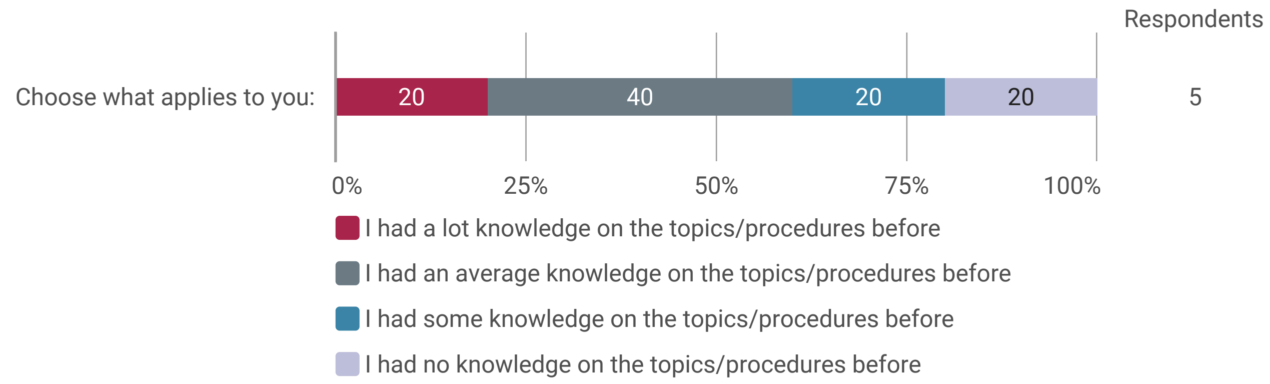
Age?

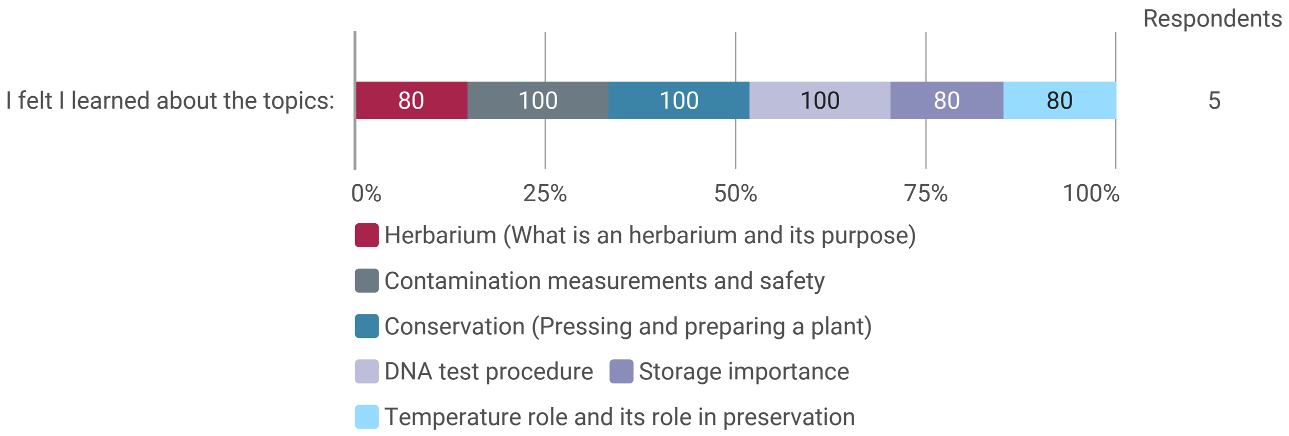

Respondents
18-23
40%
2
24-29
40%
2
30-35
20%
1
36-41
0%
0
42-47
0%
0
48-53
0%
0
54-59
0%
0
60-65
0%
0
66-71
0%
0
72-77
0%
0
78-83
0%
0
84-89
0%
0
90-95
0%
0
0%
25%
50%
75%
100%

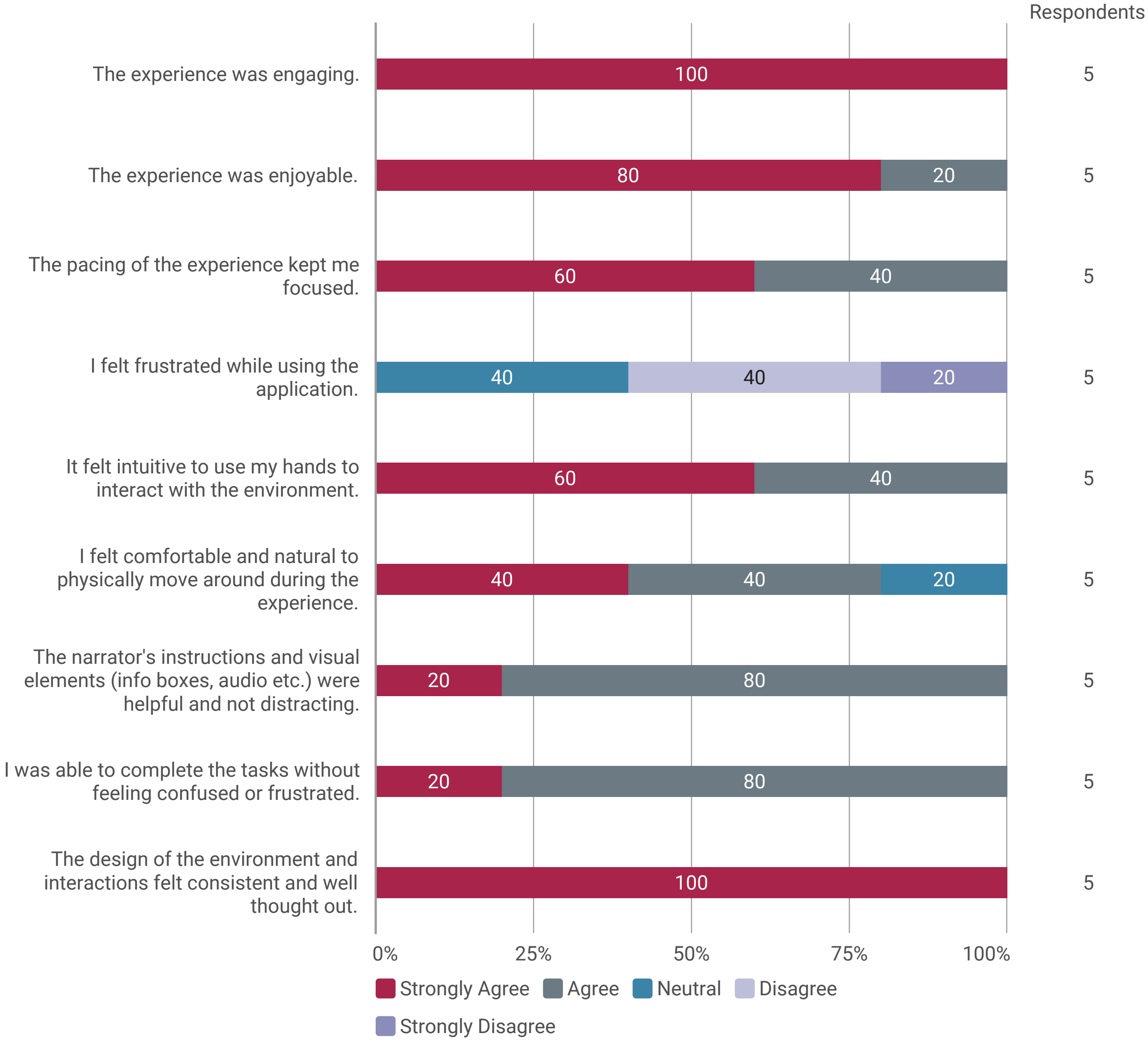

Respondents
Gender?
100
5
0%
25%
50%
75%
100%
Male
Female
Other
Prefer not to specify

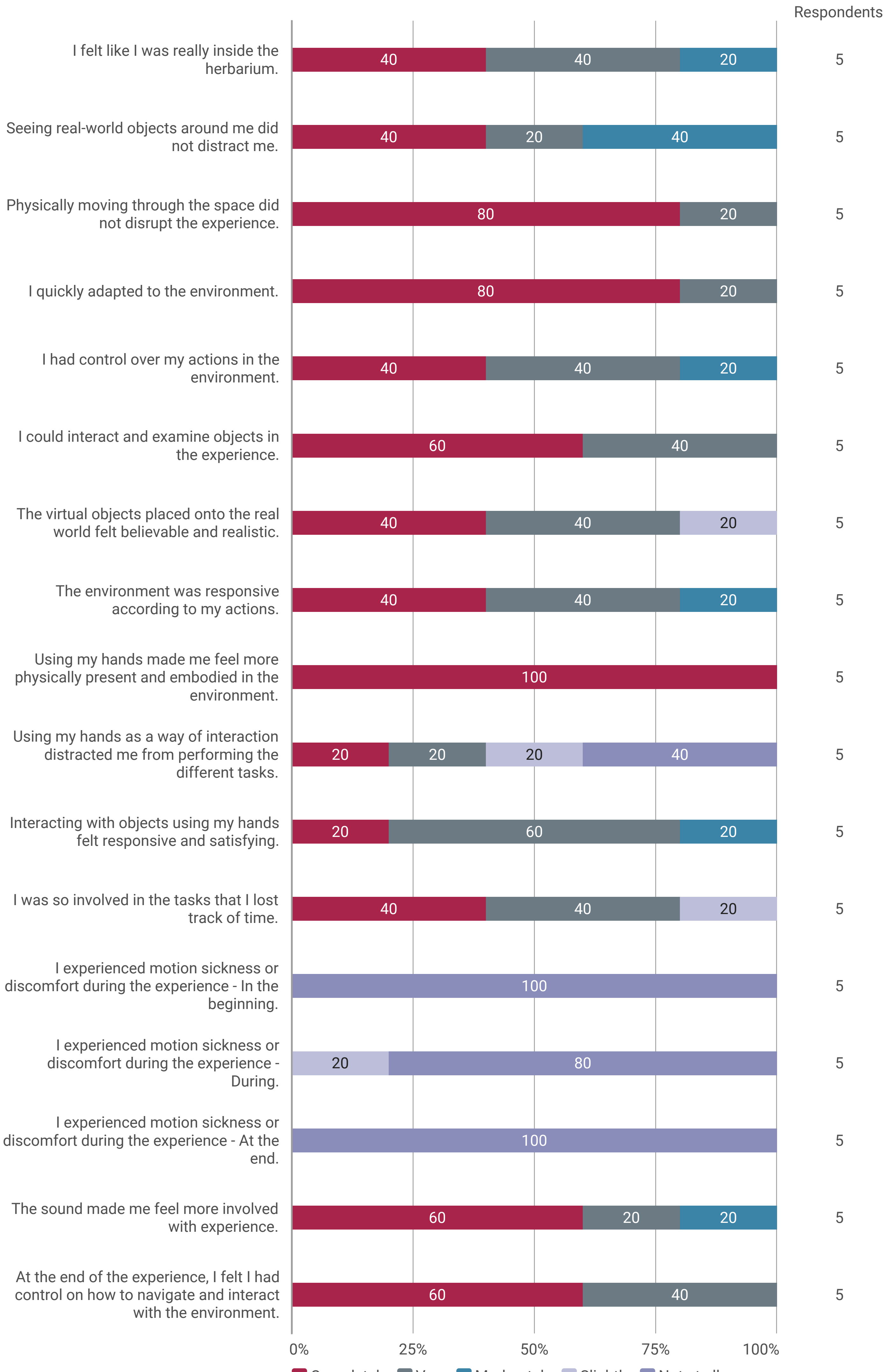

Respondents
Field of occupation?
100
5
0%
25%
50%
75%
100%
Student
Educator
Other

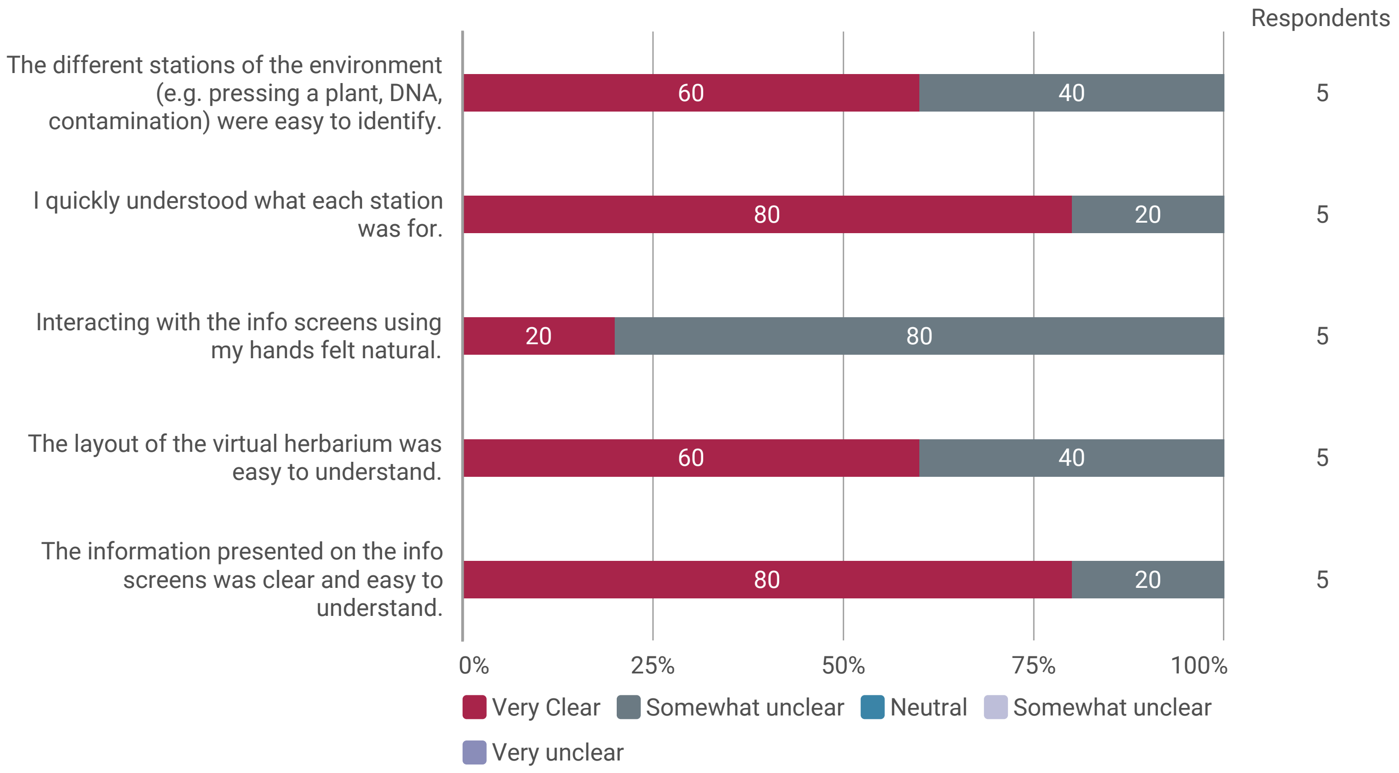

Respondents
Have you used VR/MR before?
80
80
5
0%
25%
50%
75%
100%
Virtual Reality (VR)
Mixed Reality (MR)
Never used

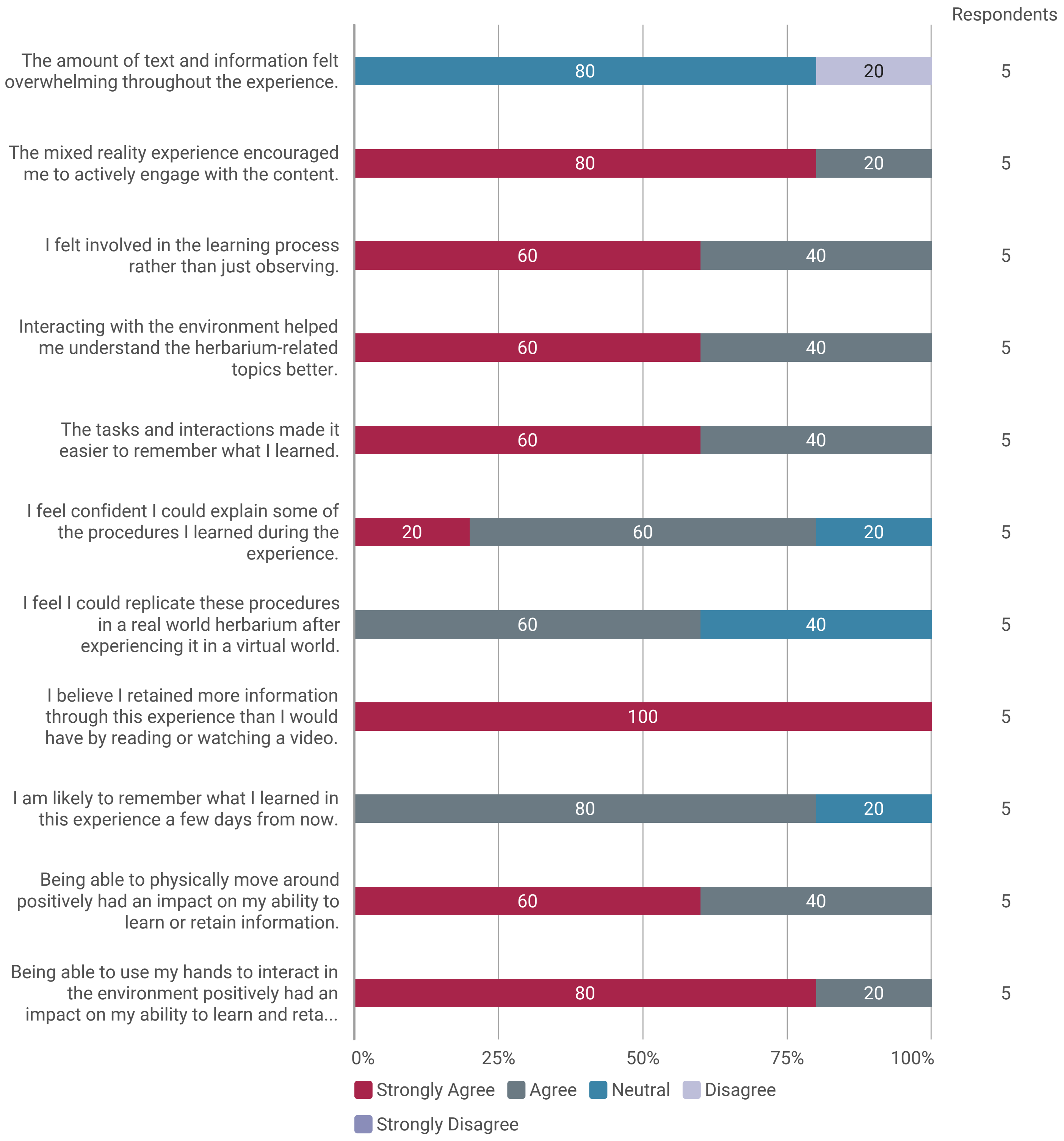

Respondents
Choose what applies to you:
20
40
20
20
5
0%
25%
50%
75%
100%
I had a lot knowledge on the topics/procedures before
I had an average knowledge on the topics/procedures before
I had some knowledge on the topics/procedures before
I had no knowledge on the topics/procedures before


Respondents
I felt I learned about the topics:
80
100
100
100
80
80
5
0%
25%
50%
75%
100%
Herbarium (What is an herbarium and its purpose)
Contamination measurements and safety
Conservation (Pressing and preparing a plant)
DNA test procedure
Storage importance
Temperature role and its role in preservation


Respondents
The experience was engaging.
100
5
The experience was enjoyable.
80
20
5
The pacing of the experience kept me focused.
60
40
5
I felt frustrated while using the application.
40
40
20
5
It felt intuitive to use my hands to interact with the environment.
60
40
5
I felt comfortable and natural to physically move around during the experience.
40
40
20
5
The narrator's instructions and visual elements (info boxes, audio etc.) were helpful and not distracting.
20
80
5
I was able to complete the tasks without feeling confused or frustrated.
20
80
5
The design of the environment and interactions felt consistent and well thought out.
100
5
0%
25%
50%
75%
100%
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree


Respondents
I felt like I was really inside the herbarium.
40 40 20
5
Seeing real-world objects around me did not distract me.
40 20 40
5
Physically moving through the space did not disrupt the experience.
80 20
5
I quickly adapted to the environment.
80 20
5
I had control over my actions in the environment.
40 40 20
5
I could interact and examine objects in the experience.
60 40
5
The virtual objects placed onto the real world felt believable and realistic.
40 40 20
5
The environment was responsive according to my actions.
40 40 20
5
Using my hands made me feel more physically present and embodied in the environment.
100
5
Using my hands as a way of interaction distracted me from performing the different tasks.
20 20 20 40
5
Interacting with objects using my hands felt responsive and satisfying.
20 60 20
5
I was so involved in the tasks that I lost track of time.
40 40 20
5
I experienced motion sickness or discomfort during the experience - In the beginning.
100
5
I experienced motion sickness or discomfort during the experience - During.
20 80
5
I experienced motion sickness or discomfort during the experience - At the end.
100
5
The sound made me feel more involved with experience.
60 20 20
5
At the end of the experience, I felt I had control on how to navigate and interact with the environment.
60 40
5
0%
25%
50%
75%
100%


Respondents
The different stations of the environment (e.g. pressing a plant, DNA, contamination) were easy to identify.
60
40
5
I quickly understood what each station was for.
80
20
5
Interacting with the info screens using my hands felt natural.
20
80
5
The layout of the virtual herbarium was easy to understand.
60
40
5
The information presented on the info screens was clear and easy to understand.
80
20
5
0%
25%
50%
75%
100%
Very Clear
Somewhat unclear
Neutral
Somewhat unclear
Very unclear


Respondents
The amount of text and information felt overwhelming throughout the experience.
80
20
5
The mixed reality experience encouraged me to actively engage with the content.
80
20
5
I felt involved in the learning process rather than just observing.
60
40
5
Interacting with the environment helped me understand the herbarium-related topics better.
60
40
5
The tasks and interactions made it easier to remember what I learned.
60
40
5
I feel confident I could explain some of the procedures I learned during the experience.
20
60
20
5
I feel I could replicate these procedures in a real world herbarium after experiencing it in a virtual world.
60
40
5
I believe I retained more information through this experience than I would have by reading or watching a video.
100
5
I am likely to remember what I learned in this experience a few days from now.
80
20
5
Being able to physically move around positively had an impact on my ability to learn or retain information.
60
40
5
Being able to use my hands to interact in the environment positively had an impact on my ability to learn and reta...
80
20
5
0%
25%
50%
75%
100%
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

Appendix O

Unity project files

VR Prototype Project Files

MR Prototype Project Files

Appendix P

Info screens text script

The content presented on the info screens within the herbarium immersive experience prototypes was developed based on references from botanical gardens and materials provided by the Natural History Museum, ensuring scientific accuracy. To enhance clarity and readability, the text was concisely refined with the assistance of AI tools [48].

Resepsjon skjerm

Tittel: Herbarium - Hva er et herbarium

Tekst:

Et herbarium er en samling av pressede og konserverte planter som brukes til forskning, undervisning og bevaring av botanisk mangfold. Herbarier er brukt som hovedmål for å studere planter, å lære seg artert, og til forskning innenfor felter som biologisk mangfold, biologisk systematikk og evolusjon [46].

Kontamineringsrom skjerm

Tittel: Kontaminering - Hvordan unngå kontaminering?

Tekst:

Kontaminering er et kritisk tema i et herbarium fordi det kan ødelegge verdifulle planteprøver og kompromittere vitenskapelig forskning. Mikroorganismer som sopp og bakterier kan spre seg og forårsake nedbrytning av materialet, mens støv og kjemikalier kan skade prøvenes struktur og farge over tid. For å bevare prøvene, er det viktig å følge strenge rutiner for håndtering, lagring og rengjøring, samt bruke riktig beskyttelsesutstyr. Å forstå og forebygge kontaminering sikrer at plantematerialet forblir intakt og tilgjengelig for forskning i mange år fremover. For å unngå kontaminering, er det best å bruke en

labbfrakk, innesko og bomullshansker for å hindre at både utstyr og prøver er i kontakt med klær som har blitt brukt utenfor herbariet [58].

Presserom skjerm

Tittel: Konservering - Hvordan presse en plante?

Tekst:

Konservering av planter betyr å ta vare på plantene i en gjenkjennbar tilstand. Dersom plantermaterialet oppbevares under gode forhold, kan det bevares i minst flere hundre år. Noe plantemateriale er bevart siden oppstarten av de første vitenskapelige herbariene. Noen av de største vitenskapelige herbariene i verden har materiale som er datert på 1600-tallet. For å bevare en plante for fremtiden må den tørkes og presses riktig. Først plasseres planten i forsiktig i pressemaskin. Deretter strammer du den slik at planten blir flat. Når den er presset, setter du hele pressen i tørkekabinetten, hvor varme og luftstrøm sørger for at fuktigheten forsvinner. Etter en viss tid er planten helt tørr og klar til å transporteres til herbarium labben [58].

LAB DNA prøve skjerm

Tittel: DNA Prøve - Hvordan ta en DNA prøve?

Tekst:

DNA-analyse brukes for å identifisere arter, undersøke slektskap mellom planter og forstå deres tilpasning til ulike miljøer. Dette er spesielt viktig for bevaring av truede arter og forskning på plantegenetikk. Før avklipping av en del av planten, er det viktig å dekontaminere pinsetet som skal brukes med bleach, destillert vann og etanol. For å teste DNA må du først hente en prøve ved å forsiktig klippe eller skrape av en liten del av planten. Deretter plasserer du prøven i en DNA-ekstraktor, som bryter ned celleveggene og frigjør DNA-et. Når ekstrasjonen er fullført, er planten analysert for å identifisere plantens genetiske kode [87].

LAB Oppbevaring prøve skjerm

Tittel: Oppbevaring- Hvordan oppbevare en plante?

Tekst:

I de fleste herbarier oppbevares de pressede plantene i ark som er sortert i esker og plassert i skap eller flyttbare reoler for å utnytte plassen effektivt.

Plantene er systematisk organisert etter art, slekt og familie, noe som gjør det enklere å finne og studere spesifike prøver. Moderne herbarier følger ofte et evolusjonært slektskapsystem fremfor tradisjonelle inndelinger basert på utseende, slik at organiseringen bedre reflekterer plantenes naturlige slektskap.

Temperaturrom skjerm

Tittel: Temperatur- Hvordan justere temperatur?

Tekst:

Temperaturen i herbariumet må holdes stabil for å bevare plantematerialet over tid. For høy temperatur kan føre til nedbrytning og økt risiko for skadedyr, mens for lav temperatur kan påvirke tørkeprosessen. En kontrollert temperatur sikrer at plantene bevares i bvest mulig stand for forskning og fremtidige generasjoner. Objekter i samlingen skal optimalt oppbevares under konstant temperatur på 18-20 grader.

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